1999 AGED REPORT

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1999**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **1999 Aged Report**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Office of the Under Secretary of Defense Acquisition and Technology Washington, DC 20301-3140**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**67**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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1. Advisory Group on Electron Devices

1.1 The Goal of the DoD Electron Device Program

Numerous credible analyses have confirmed that the technological might of the United States was directly responsible for the demise of the Soviet Union and the timely end of the Cold War. Since that time, regional conflicts have repeatedly proven that the basic DoD objective must remain unchanged:

> *To defend the nation and its interests against any adversary through the effective employment and projection of military power, whenever and wherever needed.*

We have met that objective in the past with a minimal number of personnel and weapon systems by relying on our technological might and superior weapons to provide a "force multiplication" advantage. Potent electronic and electro-optic technologies continue to power the engine of innovation that creates our technological advantage and produces superior weaponry.

The principal goal of the DoD Electron Device Science and Technology program is to ensure a highly effective approach to maintain our current military advantage, defend against technological surprise, and ensure our US military capability remains unmatched despite continuing reductions in defense spending. The achievement of this goal is key to DoD's continued ability to ensure US fighting forces rapidly prevail over any adversary in any situation.

The charts in Figure 1 indicate the DoD investment by Services and other Government agencies (e.g., DARPA, BMDO, etc.) in electron device related S&T programs during the years FY97-FY00. Figure 2 shows the DoD S&T investment during FY99 grouped by subarea and responsible DoD organization.

1.2 Mission and Functions of the Advisory Group on Electron Devices

The mission of the Advisory Group on Electron Devices (AGED) is to assist the DoD in recommending and fostering implementation of an effective investment strategy for electron device technology. The primary goal of this strategy is to ensure timely access to advanced electronic processes, materials, and devices that will enable and enhance tomorrow's technologically-superior military systems. To achieve this goal, DDR&E, with the support of the AGED, oversees the investment of limited DoD funding (usually of category 6.1, 6.2, or 6.3) to support focused research and development of those electron device technologies that ensure that the warfighter of tomorrow will dominate the battlefield. It is often possible to make use of COTS electronics in DoD systems or to develop technologies that can be applied to both commercial and military applications. These approaches allow substantial savings of recurring costs to be realized. However, the AGED recognizes that it is also essential to invest in the development of military-unique leading-edge technology developments that provide decisive battlefield advantages over adversaries. (See Appendix A for definitions of 6.1, 6.2, and 6.3 funding from OMB Circular A-11, and Appendix B for a detailed description of AGED responsibilities.)

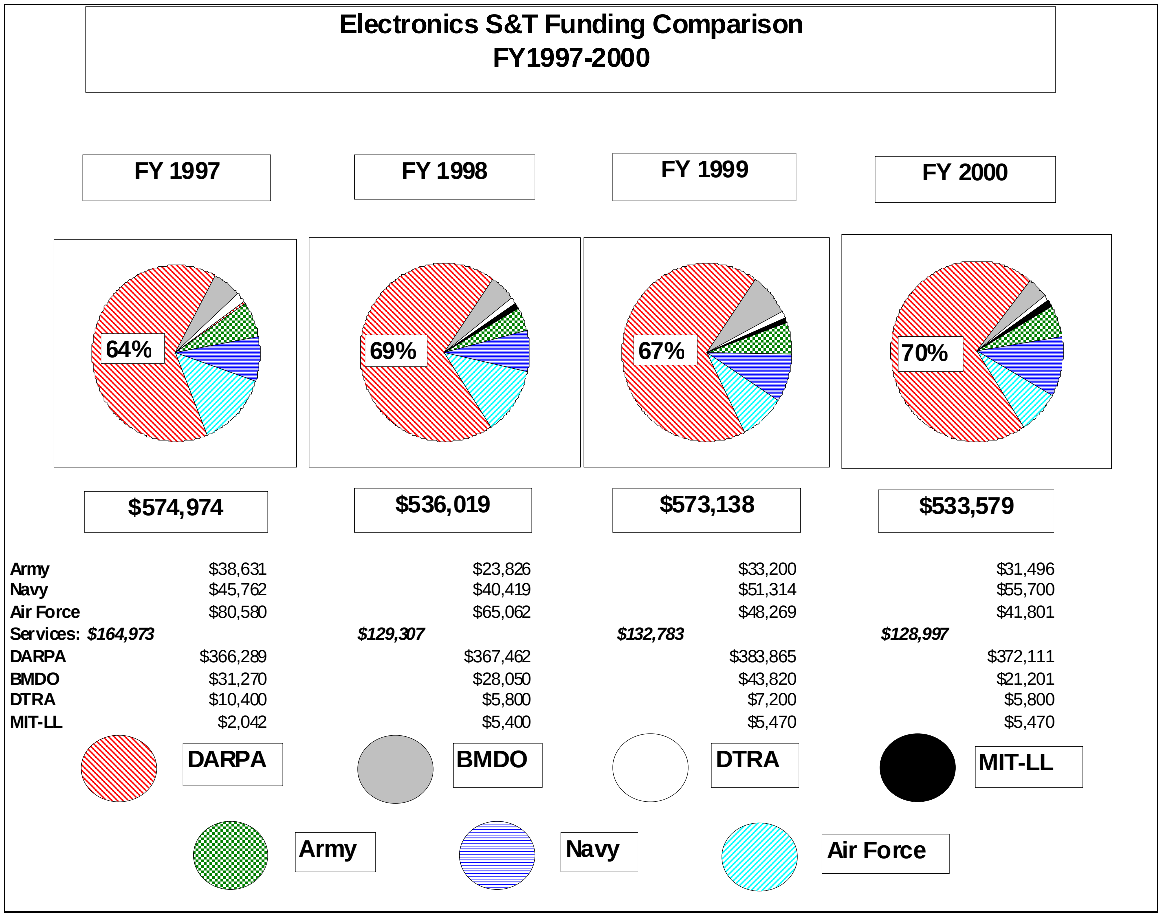


Figure 1. Electronics S&T Funding FY97-FY00

1.3 Organization and Focus of Activities

The AGED organization consists of a main group of senior managers selected from Government, industry, and academia. It functions as a steering and oversight committee for three sub-groups staffed by technical experts who are also drawn from Government, industry, and academia. The first of these subgroups, designated as Working Group A, focuses on microwaves and RF technology; the second, designated as Working Group B, focuses on microelectronics; and the third, designated as Working Group C, focuses on electro-optics. The AGED's Chairperson is Dr. Thomas Hartwick and its Executive Director is Dr. Susan Turnbach. Working Group A is chaired by Dr. Charles Krumm; Working Group B by Dr. Conilee Kirkpatrick; and Working Group C by Dr. Andrew Yang. (Employment affiliations and positions of these individuals are listed in Appendix C.) The AGED reports to the Director, Defense Research and Engineering.

AGED is sponsored by the Army, Navy and Air Force; NASA is an official co-sponsor. All of the armed services, as well as many other Government agencies, participate in AGED meetings and activities. This assures joint planning and coordination of projects and judicious expenditure of DoD resources. This is in concert with the DoD Project Reliance; Reliance Taxonomy is used as an outline for this report. AGED membership is comprised of the "best and brightest" of senior management from industry, academia, and defense organizations. Many members are Fellows of the Institute of Electrical and Electronics Engineers (IEEE) or similar

organizations and all have been accorded recognition by their peers for outstanding contributions to their profession. Members include both individuals who have served for a number of years and those who are recent additions. The diversity of experience and varied tenure of the AGED membership leads to balanced and tempered viewpoints about issues in the fields-of-interest of its three working groups and with respect to differing military-academic-industrial perspectives. Potential members are identified for their vision and talent for strategic thinking—the ability to analyze and understand contemporary practices and requirements, combined with an intimate familiarity with emerging technologies and revolutionary developments is crucial to AGED's ability to support DDR&E in charting the most effective approach to Electron Device S&T. This cadre of subject matter experts which includes both active researchers in leading-edge electronic technologies and influential leaders provides critical knowledge and insight to DDR&E regarding the DoD Electron Devices S&T program (the principal members of each Group are identified in Appendix C).

The focus of AGED activities is to observe trends and developments both within and outside of DoD to ensure optimal exploitation of DoD capabilities and externally developed advancements to advance the goals of the DoD Electronics S&T program. It is the responsibility of the DoD Electron Devices S&T program to anticipate and satisfy the technological needs of US weapon systems by providing superior processes and products at an affordable cost. The program must develop and implement a sound strategy that assures an effective transition of R&D activities from promising 6.1 projects, through 6.2 and 6.3 efforts into key processes and products for DoD systems. With the ever increasing importance of electron devices for modern weapon systems, due diligence has been and continues to be given to reducing the cost of defense electronics.

1.3.1 Broad Industry Trends

A number of trends impacting the availability and utilization of standard military electronic components, and the continued importance of military-unique electronic components for DoD systems have emerged. These trends have come about primarily as a result of the relative reduction of the military market (compared to commercial) and with the steadily declining DoD investment in research and development of military-specific electronic components. In this regard, AGED has observed the following dual trends:

COTS Components and Infrastructure

DoD now has very limited influence on the electronics component industry since the dollar value of military electronics components sales is < 1% of total sales. Without direct DoD financial support, it is highly unlikely that commercial suppliers will develop military unique components or customize existing commercial-off-the-shelf (COTS) components in order to meet military performance specifications. Therefore, DoD is strongly tending towards a COTS strategy consisting of:

- Maximizing the use of low cost COTS components where appropriate—"making do" with commercially available parts, for which there is no serious system/mission performance penalties for doing so. In addition, the DoD is hoping to provide an advantage over its military adversaries by incorporating special architectures and features at the system level, even with COTS component implementation.
- Utilizing standard commercial specifications for components and manufacturing line certification.

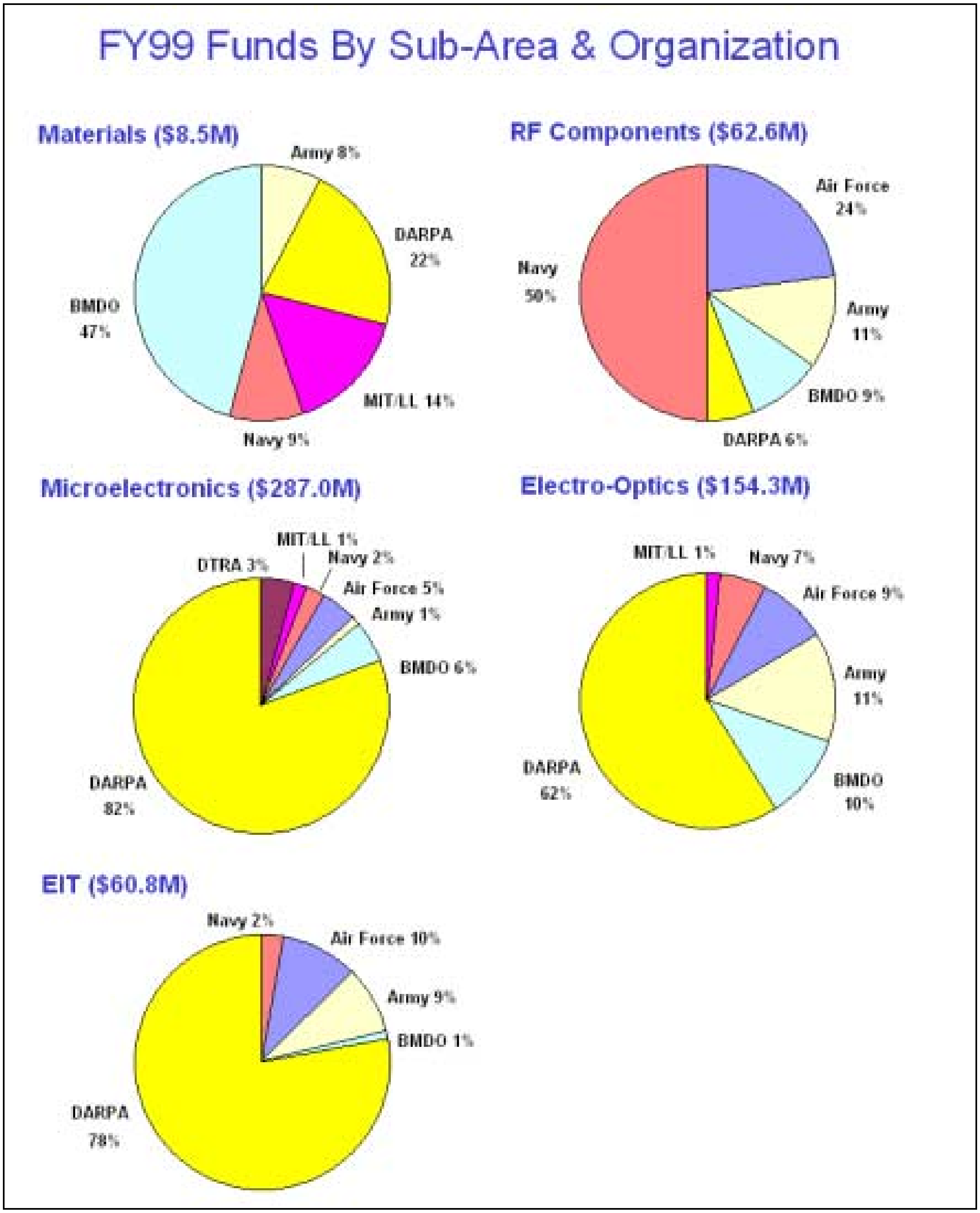


Figure 2. FY99 Funding by Subarea and Organization

Military Unique Electronic Components and Technologies

Development of specific custom electronic components is still very critical for preserving DoD system superiority versus that of our adversaries. These components are, in general, no longer digital integrated circuits but rather advanced microwave/millimeter wave frequency analog integrated circuits, analog-to-digital converters, specialized electro-optical devices, devices and components for operation at very high temperatures, advanced antennas and high performance, highly integrated packaging and interconnect approaches, particularly for use at frequencies above 1 GHz. There are many military sensor and weapon situations where better resolution, standoff distance, nonobservable penetration, etc. are absolutely critical to defense system superiority. Often, achieving these superior weapon performance parameters is directly traceable to superior electron device technology.

Industry has begun to develop a degree of anti-DoD business bias; i.e., since the overall DoD electronic components business is very small and the potential return on investment limited, some suppliers will only accept DoD funding if the product DoD desires is expected to eventually also have significant commercial sales. It is imperative that DoD continues to make these necessary R&D investments. AGED anticipates a continued high potential payoff from significant advances in certain military critical components.

In order to better understand the role of COTS in DoD systems, AGED sponsored a Special Technology Area Review (STAR) on COTS technology in late 1997. It was found that, although there is no question that it is prudent to use COTS components to the maximum extent possible, many of the COTS components that are used in today's military systems can trace their heritage to DoD-sponsored research and development programs. AGED recognizes the benefits of reduced cost and, in some cases, increased performance that is available from commercially developed products. Therefore, in its advisory role, AGED has advocated the judicious use of COTS in defense systems. Meeting the need for high performance electron devices will depend increasingly on adaptation of existing commercial technology, development of technologies with dual use applications, and fewer, but nonetheless critical, requirements to develop military-unique technologies.

Details regarding the findings and recommendation of this STAR are provided in Section 3.1 of this report.

1.4 Projected Military System Requirements

Electronics technology has become essential to every aspect of U.S. defense and is widely recognized as the most rapidly advancing technology area. Work during the past several years has led to the widespread use of microwave monolithic integrated circuits (MMICs) in both military and commercial systems, greatly increased capabilities for digital signal processors and memories, new types of lasers including ones that emit blue light, proliferation of both miniature and large flat-panel displays as replacements for cathode ray tubes and numerous promising laboratory results for various types of Micro-Electro-Mechanical Systems (MEMS). Technology advances such as these will be accompanied by significant reductions in both acquisition and life cycle costs per unit of capability. System and subsystem performance improvements and life cycle cost reductions will occur primarily from advancements in highly integrated computer-aided-design capabilities combined with rapid, cost-effective production of the increasingly

sophisticated materials, devices, circuits, and hybrid assemblies required by future weapon systems.

Highly efficient radio frequency, electro-optic, and microelectronic technologies are the building blocks from which we craft the ever vigilant “eyes, ears, and brain” of today’s defense systems. The most potent “weapons” of modern defense, such as those identified in Table 1, demand substantial improvements in electronic technology if they are going to continue to be capable of defending our country in the 21st century.

AGED has identified several key technical capabilities that will shape the future of military conflict. Further information about the relevant capabilities that those technologies provide is available in Appendix D; a summary of the required capabilities is provided here.

- High Performance Microwave and Millimeter Wave Integrated Circuits
- High Resolution, Wide Bandwidth Analog-to-Digital Converters
- Photonic Solutions for Active Multi-Sensor Arrays; Computing and Memory
- High Performance Microelectronic Materials, Devices and Circuits for High Temperature and Adverse Environment Operation
- Radiation-Hardened Electronics
- Maturation of Critical Technologies Prior to Production
- High Resolution Miniature Displays
- Cooled and Uncooled Focal Plane Arrays
- Compact, High Power Lasers
- Microelectromechanical Systems (MEMS)
- Mixed-Signal Integrated Circuit Technologies
- Power Conversion/Power Distribution Technologies
- Enhanced Computer Language and Modeling

Table 1. Tools and Technology of Modern Defense

TOOLS OF MODERN DEFENSE	CRITICAL FUNCTIONS AND TECHNOLOGIES
Radar	Active Electronically Scanned Arrays, Seekers, Synthetic Aperture, Low Probability Of Intercept, MMICs, A/D converters, Advanced microwave packaging, Photonic and Optical Components.
Electronic Warfare	High Power Lasers for IRCM, Optical And Electronic Countermeasures Components, Jammers, Radar-Warning Receivers, Signal Processing Circuits
Platform/Weapon Control	Fusing, Guiding, Actuating, Sensing, Controlling, And Navigating
Computation	Analog-To-Digital (A/D) Converting, Signal Processors, Data Processors, Memory, Programming, Hardware Implemented Algorithms
Imaging	Staring And Scanning Focal Plane Arrays, Image Processing, Enhancing, IR Detectors
Communications	Satellite, Tactical, Secure, Fiber-Optic, Wideband, MMICs, A/D Converters, Photonics, Lasers

To provide these capabilities, OSD and the Services, with the guidance and support of AGED, have crafted an electronic technology development program that ensures the availability of key technologies needed to develop/enhance warfighter capabilities. Examples of these capabilities are all weather day/night precision weapon delivery with low collateral damage, superior tactical and strategic intelligence, denial of such intelligence to the enemy, UAV-required technologies, and advanced components for self-protect jamming and electronic warfare. Assured and sustained DoD investment at an appropriate level will lead to dramatic improvements in information system capabilities in the future. Enhanced capabilities afforded by the DoD electronic technology development program will enable objectives such as the following to be accomplished:

- Quickly providing needed timely information to forward-deployed units
  - Rapid collection, analysis, and dissemination of strategic, tactical, and logistical information to afford commanders a common view of the tactical situation
  - Enhancement of the tempo and synchronization of joint warfighting operations through shared situational awareness
  - Reduction of personnel requirements—both staff and non-combatant.
- Reducing operating and support (O&S) costs by a factor of 10 or more and extending the life and interoperability of existing fielded systems.
- Providing significant performance improvements and new warfighting capabilities.
- Providing new generations of sensors, sources, actuators, and display technologies, leading to unprecedented capabilities in land, sea, and air warfare.

Although required investments will continue to be substantial, the payoff will be enormous in terms of the savings accrued in both acquiring and maintaining superior military capabilities.

1.5 AGED Activities

1.5.1 Special Technology Area Reviews

Special Technology Area Reviews (STARs) have become key AGED activities. Bringing together both AGED and non-AGED participants (invited experts from industry, academia and Government), these comprehensive reviews are concentrated one or two-day meetings that focus on specific major issues in electronic technology. Organized by one of the AGED groups as appropriate subjects arise, STARs provide a direct and effective way to conduct highly focused technology assessments leading to the ability to provide informed guidance to the DoD. The STAR reports reflect extensive consideration of technical and programmatic issues in the context of DoD's overall military electronics requirements. STAR reports have played an important role in identifying electronics technologies that resulted in great advances in DoD system capabilities. In general, these technologies showed great promise but required substantial, focused S&T investments in order to reach an appropriate level of maturity for viable DoD system use. STARs also expose weaknesses and potential producibility aspects that impact the optimum implementation of new technologies. Major initiatives that have stemmed from AGED recommendations include VHSIC, MIMIC and IRFPA Producibility. As a result of other STARs, increased emphasis was placed on the development of Vacuum Electronics and Frequency Control Devices.

Between 1996 and mid-1999, AGED STAR reports were issued addressing:

- Commercial Off-The-Shelf (COTS) Electronic Components
- Frequency Control Devices
- Optical Interconnect Technology
- Micro-Opto-Electro-Mechanical Systems (MOEMS)
- Infrared Countermeasure (IRCM) Lasers

More detailed descriptions of these STARs and their findings/recommendations may be found in Section 3.

1.5.2 TARA Involvement

The Electronics portion of the Technical Area Review and Assessment (TARA) was held this year between March 1 and 5, 1999 in Monterey, CA. This meeting, one of several held annually by the DoD to assess progress in various technology and system areas, affords the opportunity for experts from outside the DoD to offer their recommendations concerning how well the overall electronics program is meeting DoD needs and how the value of DoD's Science & Technology investments can be maximized. Three AGED members, Dr. Conilee Kirkpatrick, Chairperson, Working Group B, Mr. James Clary, Member of Working Group B and Dr. William Tennant, Member of Working Group C were members of the 1999 Electronics TARA team. Their guidance and recommendations were forwarded to the Defense Science and Technology Advisory Group (DSTAG) for consideration after the TARA meeting.

1.5.3 Interaction with TPED

Although AGED does not directly participate on the Technology Panel for Electron Devices, it is available for consultation and technical support and recommendations, upon request. In particular, during the past several months, the Services have been engaged in preparing "roadmaps" for fourteen of the major electronics technology areas. The drafts of these roadmaps have been presented at AGED meetings and the AGED membership has provided suggestions as to how they can be made more useful for DoD S&T program planning as well as providing connectivity to industry efforts. The AGED provides counsel on the value of technology efforts currently being undertaken as well as suggesting promising new technology areas, recommends strategies that will lead to maximum benefit to the DoD at a minimal cost, identifies key areas which lack adequate support, recommends an appropriate balance between investment in revolutionary and evolutionary technologies and provides suggestions for appropriate entrance and exit criteria.

1.5.4 AGED Meetings Held

During the past year, AGED Main Group has held six meetings. Each working group, Working Group A, B, and C has also held five or six meetings in 1999. During these meetings, detailed discussions are held on a variety of current issues including recent breakthroughs in the state-of-the-art of relevant technologies, problem areas demanding attention, approaches for improving the DoD Science and Technology (S&T) investment strategy, responses to requests for information from OSD and the Services and how to meet DoD system needs more effectively. Every meeting includes a review of recent technical, company and budget-related articles from relevant technical journals and trade magazines. Most meetings include one or more presentations by experts in various technology areas to keep members abreast of changing technology trends and opportunities for S&T investment. Others include interactions with

system developers to define future system needs for electronics, major projects in other Government agencies, or detailed examination of an ongoing program. Most meetings are held in the Washington, DC area but occasionally the Advisory Group conducts first-hand reviews at various DoD and DoE laboratories, such as Sandia National Laboratory. These on-site meetings serve the dual purpose of allowing the Advisory Group to interact informally with a broader base of Government scientists and engineers at the meeting location and keep the AGED abreast of the latest scientific research and development activities being conducted by these organizations.

1.5.5 Coordination Activities

AGED's role has changed dramatically over the past ten to fifteen years. Up until the mid-1980s, it was responsible, by directives from the military Departments, for assuring the coordination of individual technical work units between the Services. This assured that newly proposed programs were not only technically sound but also would avoid unnecessary duplication of technical effort. However, during the mid-1980s, this coordination process was suspended because of procurement-related concerns. Although, it was later restored, the Services have increasingly shifted their method of contracting for scientific research and development from the use of Requests for Proposals (RFPs) to use of Broad Agency Announcements (BAAs). By their nature, BAAs define broad topics of interest which, without detailed specifics, are difficult to evaluate. Since the late 1980s, much of the responsibility of coordinating inter-Service electronics programs has been assumed by Project Reliance, Technical Panel on Electron Devices (TPED). However, the AGED assists the TPED, both directly and indirectly, in its efforts to avoid unwarranted program duplication. This assistance includes independent counsel by the AGED consultant members from industry and academia during AGED meetings and through guidance to the Services during their preparation for the TARA. TARA assistance has included a critical review of all of the major presentations, prior to the TARA, and providing guidance that resulted in the presenters being better able to convey the key points of their briefings to the TARA team members.

2. Significant Achievements

The following are brief accounts of recent significant achievements in each subarea of electron and electro-optic device technology and supporting materials research.

2.1 RF Components

2.1.1 The Microwave and Analog Front End Technology (MAFET) Program

1999 is the final year of the MAFET program. This four-year, $115M program has resulted in major advances in the state-of-the-art and availability of microwave monolithic integrated circuit technology.

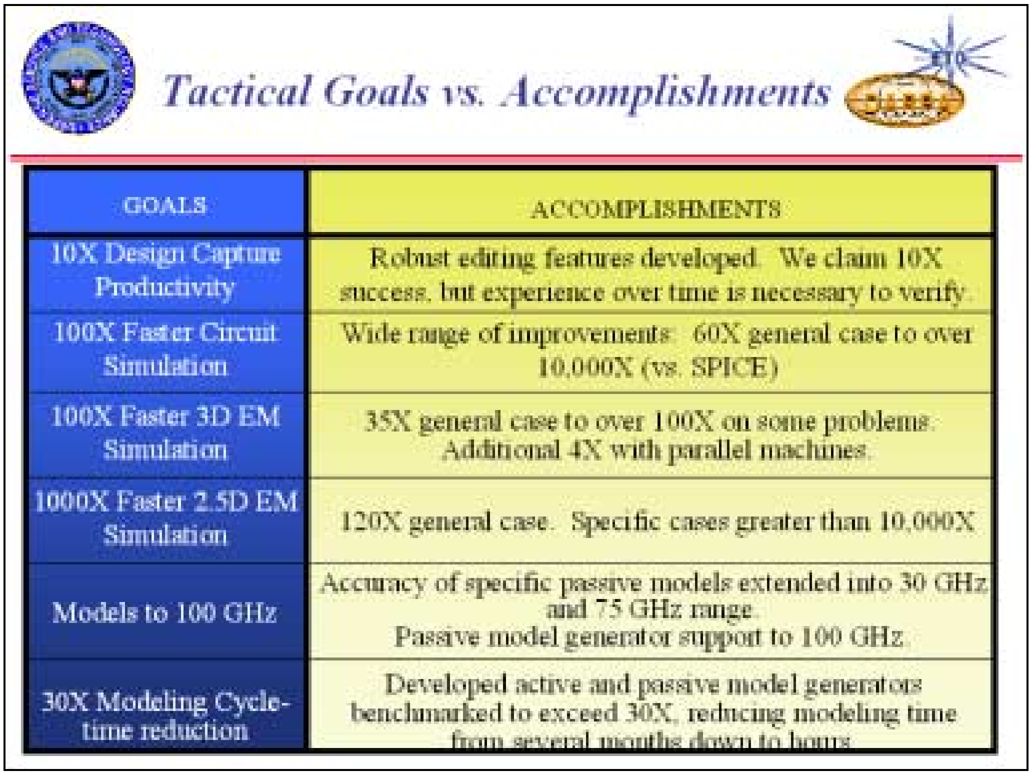
Virtually every RF solid-state technology area has benefited from advances achieved under this program. For example, high quality, low cost GaAs and InP substrates are now commercially available for manufacturing RF, mixed-signal, digital and optoelectronic components. Work is progressing on the development of new material systems such as silicon carbide (SiC), silicon germanium (SiGe), and gallium nitride (GaN). These wide-band semiconductors operate well at high temperatures and lead to devices with the capability of supporting high power densities.

New and improved computer aided design (CAD) tools and tools for simulation of microwave and millimeter wave components have become available commercially. The design cycle time for a typical military system MMIC and related modules that make use of those MMICs has been reduced to one-third of that needed at the beginning of the MAFET program in 1995. Non-recurring engineering costs have also declined markedly and the number of iterations necessary to produce a typical MMIC circuit that meets its specifications has declined from more than four passes to one-and-a-half passes. Figure 3 provides a comparison between MAFET design capability goals and accomplishments.

A significant number of GaAs and InP MMICs have been demonstrated as well as millimeter-wave frequency multi-chip assemblies that provide high performance at frequencies up to 94 GHz (see Figure 4).

MMIC manufacturing has also improved markedly with the achievement of much better yields of millimeter wave circuits including both low-noise and high power GaAs and InP based products. Millimeter-wave multi-chip assembly and packaging capabilities have also enjoyed major advances.

Significantly improved results were also obtained for wide bandgap devices fabricated from silicon carbide (SiC) and gallium nitride (GaN). Figure 5 shows a recent result for a SiC MESFET amplifier.



Tactical Goals vs. Accomplishments

GOALS	ACCOMPLISHMENTS
10X Design Capture Productivity	Robust editing features developed. We claim 10X success, but experience over time is necessary to verify.
100X Faster Circuit Simulation	Wide range of improvements: 60X general case to over 10,000X (vs. SPICE)
100X Faster 3D EM Simulation	35X general case to over 100X on some problems. Additional 4X with parallel machines.
1000X Faster 2.5D EM Simulation	120X general case. Specific cases greater than 10,000X
Models to 100 GHz	Accuracy of specific passive models extended into 30 GHz and 75 GHz range. Passive model generator support to 100 GHz.
30X Modeling Cycle-time reduction	Developed active and passive model generators benchmarked to exceed 30X, reducing modeling time from several months down to hours

Figure 3. MAFET Thrust 1 Goals versus Accomplishments

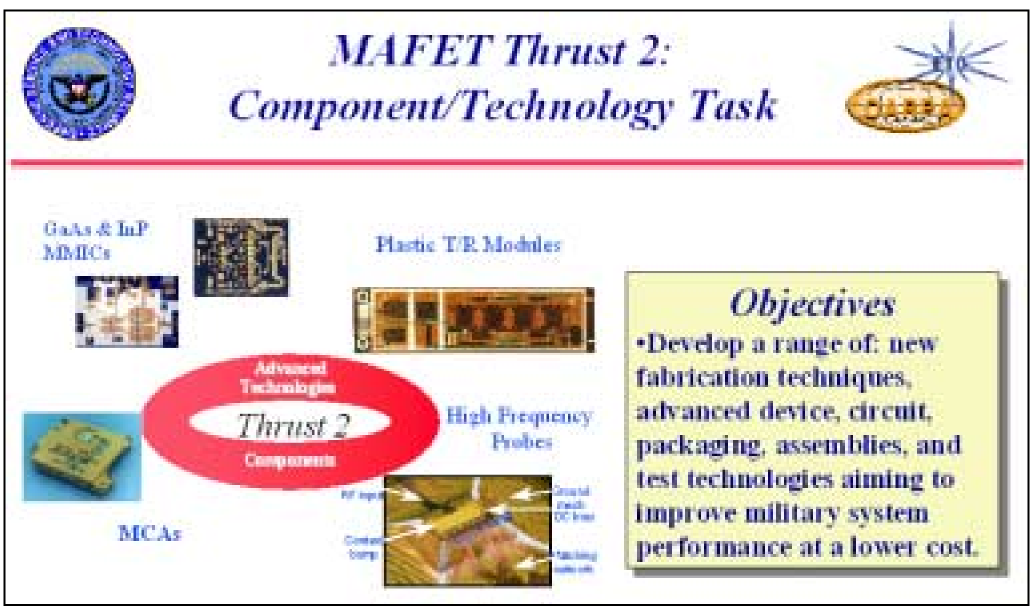


Figure 4. GaAs and InP MMICs Developed under MAFET

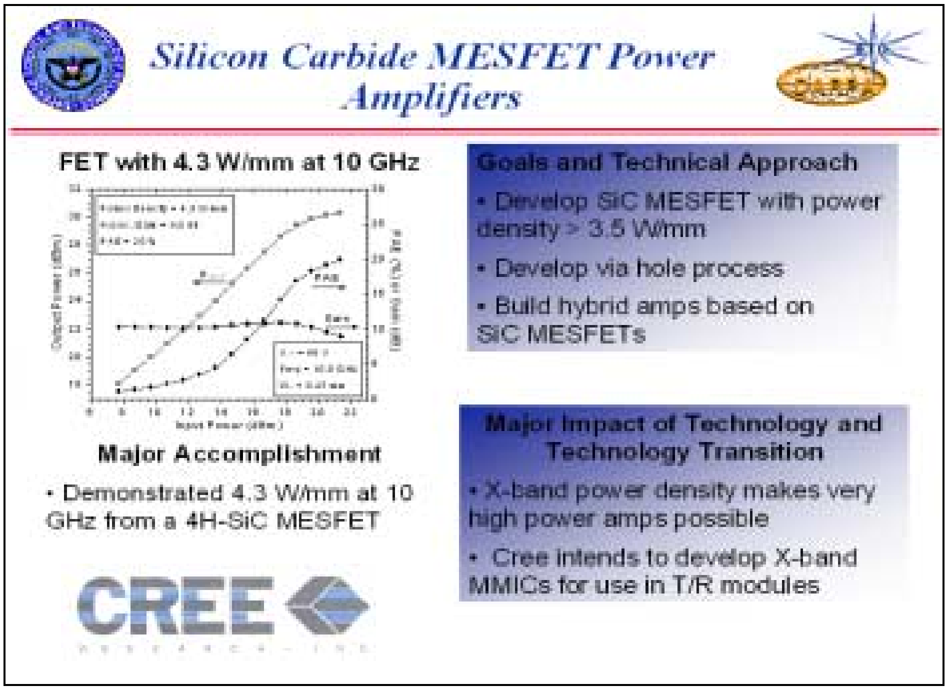


Figure 5. SiC MESFET Power Amplifiers

2.1.2 High Power Millimeter-Wave Vacuum Electronics

Millimeter wave radar and high power jamming applications have been significantly advanced with the development of millimeter-wave vacuum electronics technology. Extremely high peak and average power has been achieved from a gyro-klystron operated at 94 GHz. Over 80 kW of peak power and approximately 10 kW of average power has been achieved from a device of the type shown in Figure 6. This has important implications for applications such as millimeter-wave jamming and radar systems.

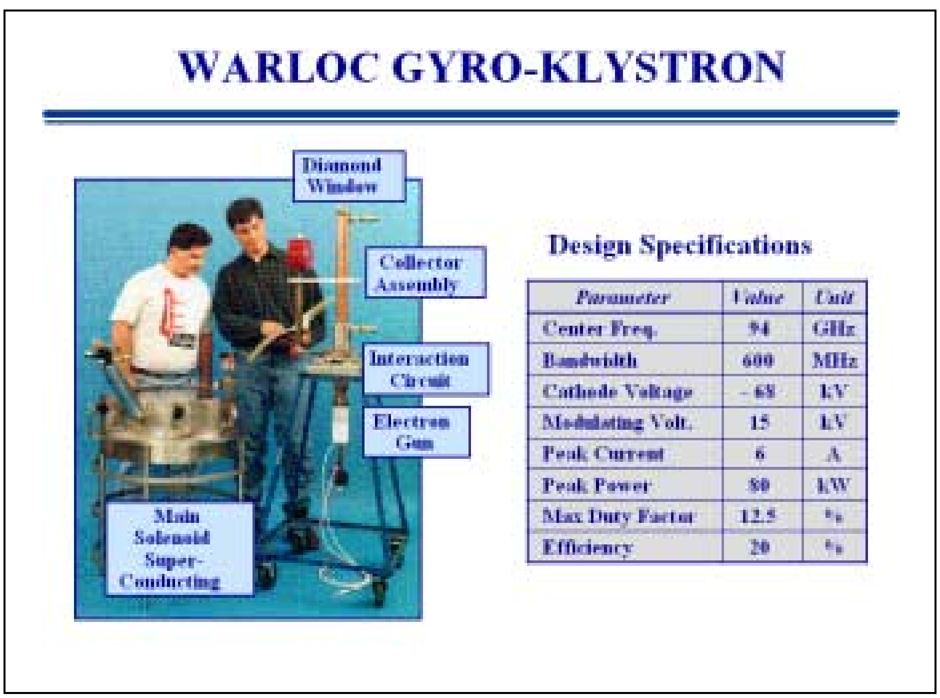


Figure 6. WARLOC Gyro-Klystron

2.1.3 Millimeter Microwave Power Module (MMPM)

Work is continuing on the development of a millimeter-wave microwave power module (MMPM) incorporating a solid state driver, a vacuum electronics micro-TWT power booster, and an integrated power conditioner. The MMPM will improve present TWT reliability in the millimeter wave region and significantly reduce the cost of future MMW radar and communications systems. Unfortunately, funding limitations have prevented work on this important component from being completed. Figure 7 summarizes the objectives of the MMPM program.

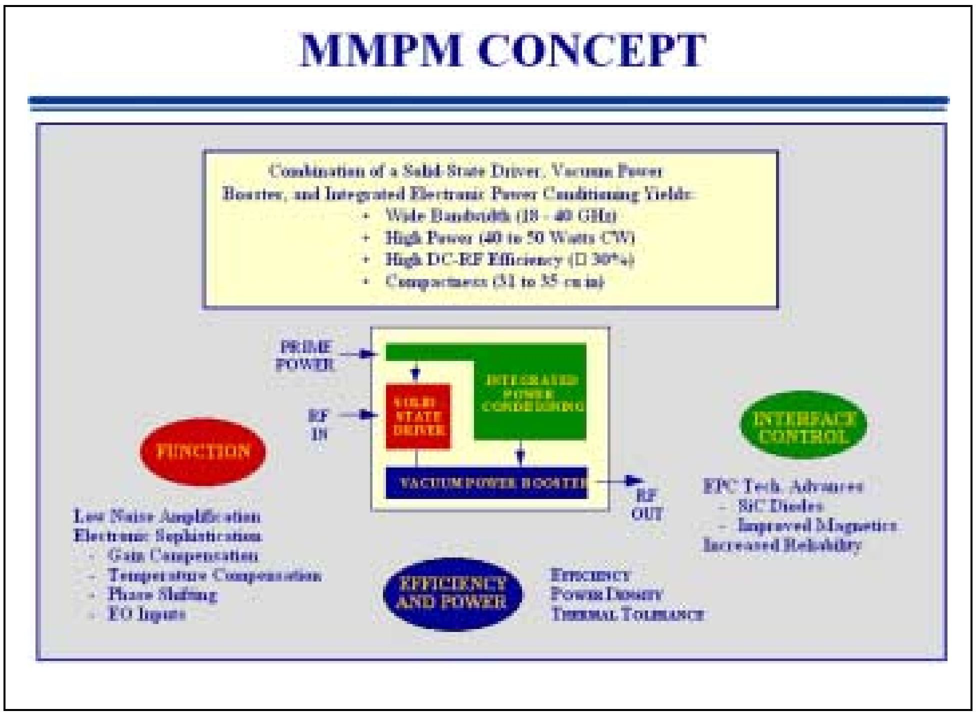


Figure 7. MMPM Program Concept

2.1.4 Advanced Antennas for Space Communications, Target Detection and Tracking

New antenna technology is being developed to meet the increased emphasis on space platforms and the need for efficient target detection and tracking (see Figure 8). The tri-Service activity exploits three fronts in antenna technology, developing low-cost mechanical scanning systems where feasible, and the most advanced phased array hardware and digital control where it is advantageous. Figure 8 highlights these three thrusts, showing a mechanically scanning antenna, a group of advanced phased arrays, and a concept view of the tri-Service DTO on digital beamforming technology.

The low profile mechanically scanned antenna system is being developed for airborne SATCOM from large aircraft. These antennas provide higher data rate and wider scan coverage at lower cost than phased arrays. Phased arrays are well suited for high performance low-observable aircraft. They were initially developed by the Air Force and transitioned to the Navy and to commercial applications, and are now candidate SATCOM antennas for the B-2. Figure 8

shows the initial Air Force 20- and 44-GHz arrays and a larger 20-GHz array developed by the Navy.

DTO SE.63 is a tri-Service program that exploits the capabilities of digital beamforming at the antenna level by developing algorithms for element correction and advanced sub-arraying, and at the processing level by investigating sub-banding techniques to provide wideband coverage.

Current plans include demonstration of lightweight reconfigurable multi-band phased array antenna technology for all three Services, and the integration of Micro-Electromechanical-Systems (MEMS) phased array antenna systems to produce reduced size, weight, power, electronically agile multi-beam antenna sensors.

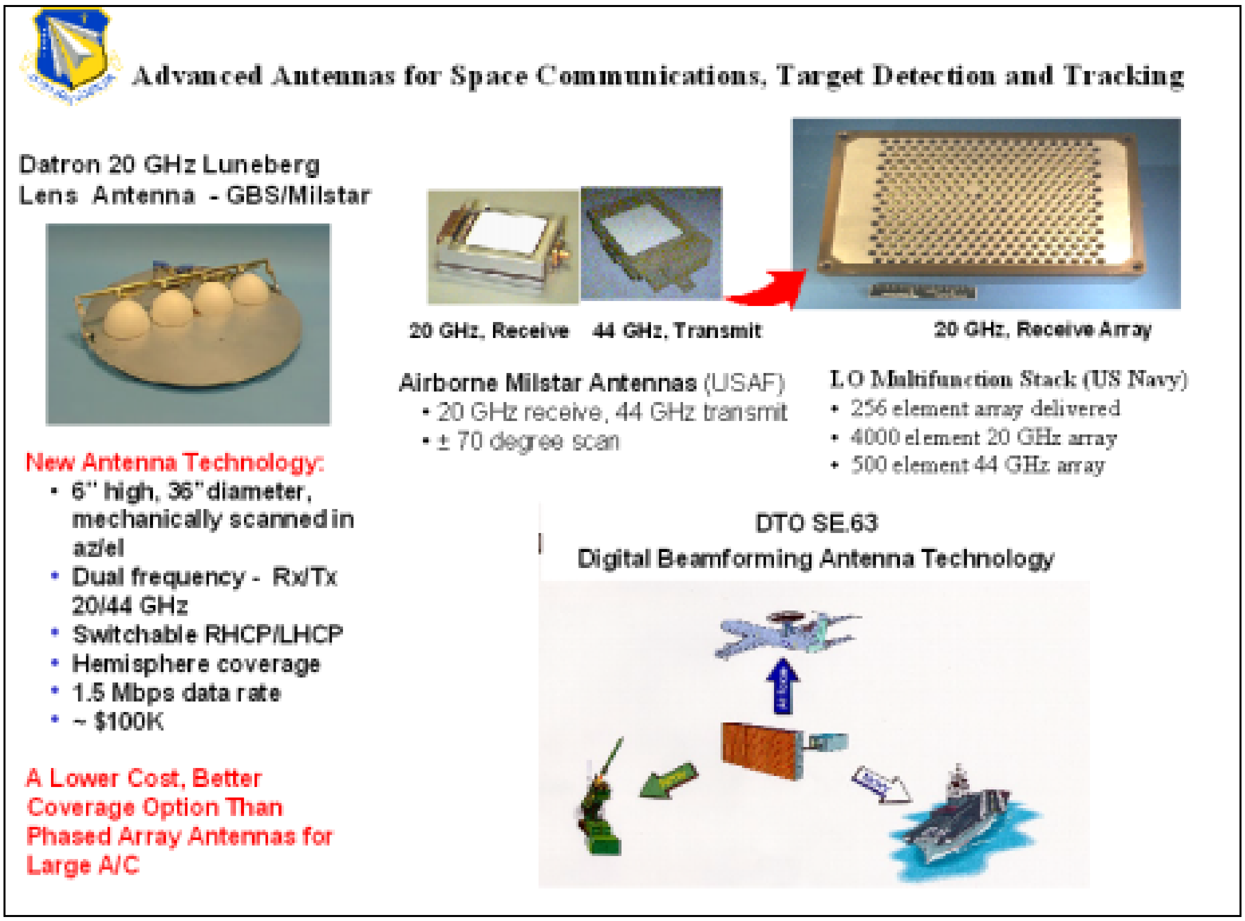


Figure 8. Advanced Antennas for Space Communications, Target Detection and Tracking

2.1.5 Frequency Control Devices

Very precise, compact, low-cost frequency control devices are needed for such important applications as GPS and airborne/vehicle mounted radars. During the past few years, important advances have been made in the development of recently invented materials such as langasite, langanite, and langatate. Already showing a “Q times frequency” factor of 50 million, which is about five times that of quartz, these materials promise improved crystal oscillator stability in compact, low-cost packages, improved phase-noise performance, and improved low-loss filter performance. The boule of langatate material shown in Figure 9 is representative of this work. Measured Q x F values are shown in Figure 10.

Another achievement is a factor-of-ten reduction of the vibration sensitivity of quartz resonators, achieved by a new cantilever design of the resonator, which is illustrated in Figure 12. Figure 11 shows that there is a range of cantilever overhangs for which the vibration sensitivity approaches zero. Reduction of vibration sensitivity is important for vehicle-mounted (including airborne) MTI radars, to minimize masking of slow-moving targets by vibration-induced phase-noise sidebands.

Figure 9. Langatate Boule Developed at Crystal Photonics Inc. by ARL/CECOM for Acceleration-Insensitive Clocks

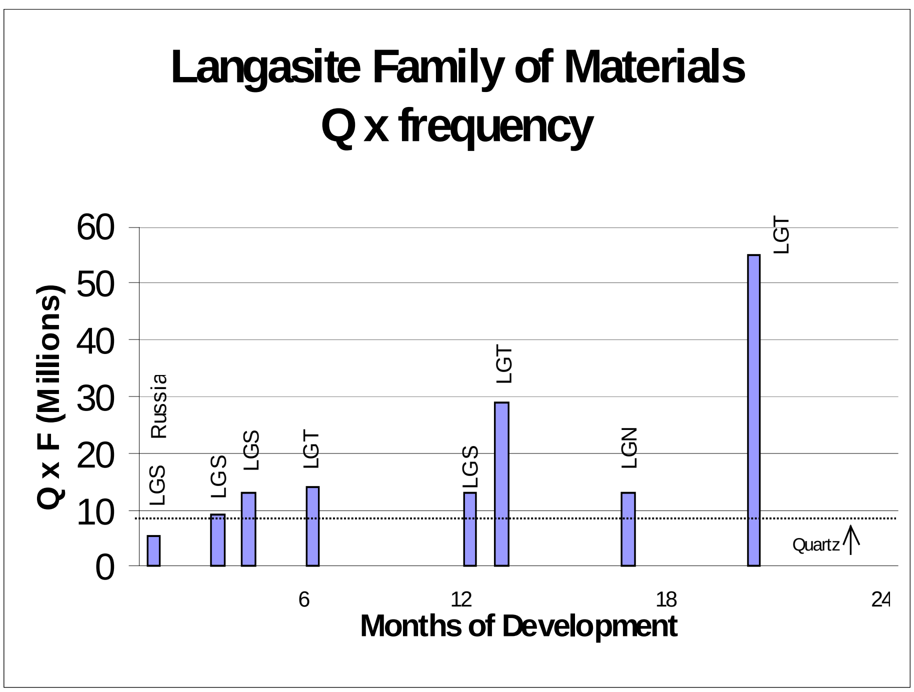


Figure 10. Langasite Measured Q x F Values

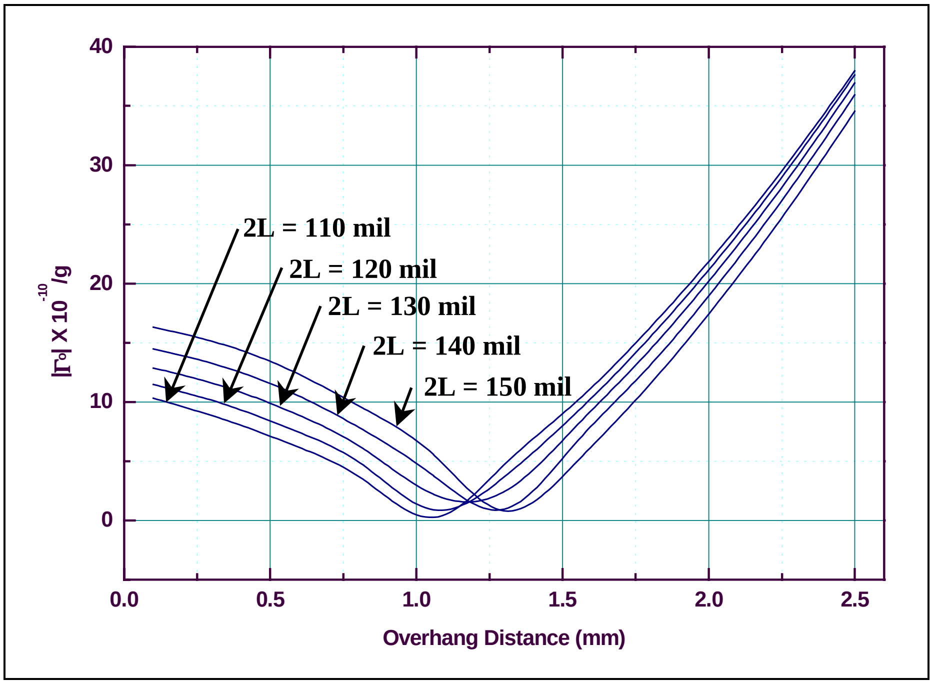


Figure 11. Overhang Distance versus Vibration Sensitivity

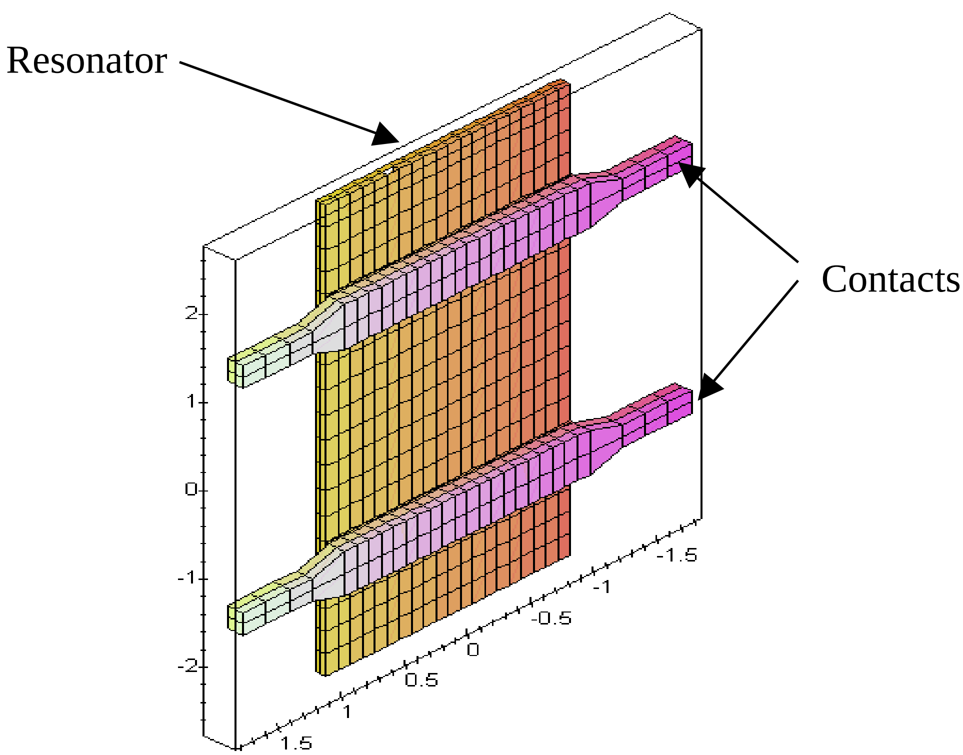


Figure 12. New Cantilever Design for Quartz Resonators

Another significant achievement is the invention of optoelectronic oscillators that combine low-loss optical fiber delay lines with other optical techniques to generate microwave frequencies with phase noise of –140 dBc/Hz at 10 kHz from a 10 GHz carrier. This is the highest spectral purity demonstrated by any open-loop oscillator at this frequency.

2.2 Microelectronics

Technologies grouped into the Microelectronics category of the DoD Electronics Taxonomy include radiation hardened circuits, analog-to-digital converters, micro-electro-mechanical systems (MEMS), advanced lithographic techniques and low power electronics as well as mainstream silicon technology. Significant advances have been achieved in many of these areas this year under DoD S&T funding as described below.

2.2.1 Digital Receivers and Analog-to-Digital Converters

The successful development and fielding of digital receivers is expected to provide greatly enhanced capabilities for communication, radar and electronic warfare systems. Some promising prototypes have already been developed but they do not yet meet the requirements for DoD system applications. Digital receivers for communication systems are being developed with commercial funding because of the potential for significant sales. However, for radar and electronic warfare systems, DoD funding is essential. The most critical component of these receivers, yet to meet required performance specifications, is the analog-to-digital converter. To allow systems to meet their overall performance requirements, analog-to-digital converters for radar systems must have a large number of effective bits, operate over a large spur-free dynamic range and across a significant frequency bandwidth. Electronic warfare systems require analog-to-digital converters with a similarly large number of effective bits and spur free dynamic range of operation but with the ability to operate over an even larger band of frequencies. Figure 13 summarizes many of the advantages that will accrue from the use of next-generation broadband digital receivers. These include greatly reduced size and total power requirements.

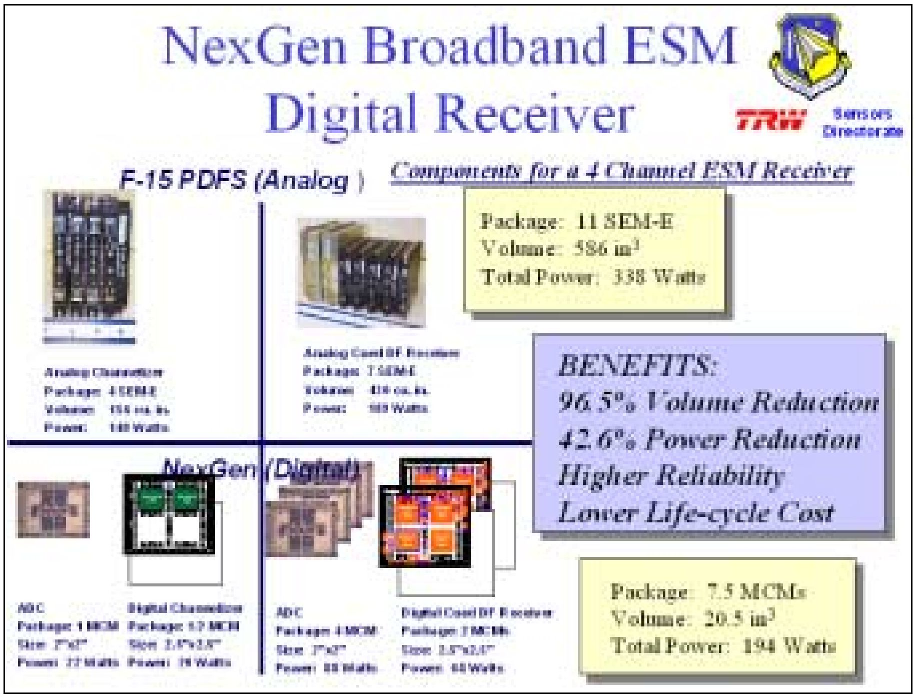


Figure 13. Next Generation Broadband Digital Receiver

Figure 14 is a compendium of achieved analog-to-digital converter results and includes the goals of current DoD analog-to-digital converter programs.

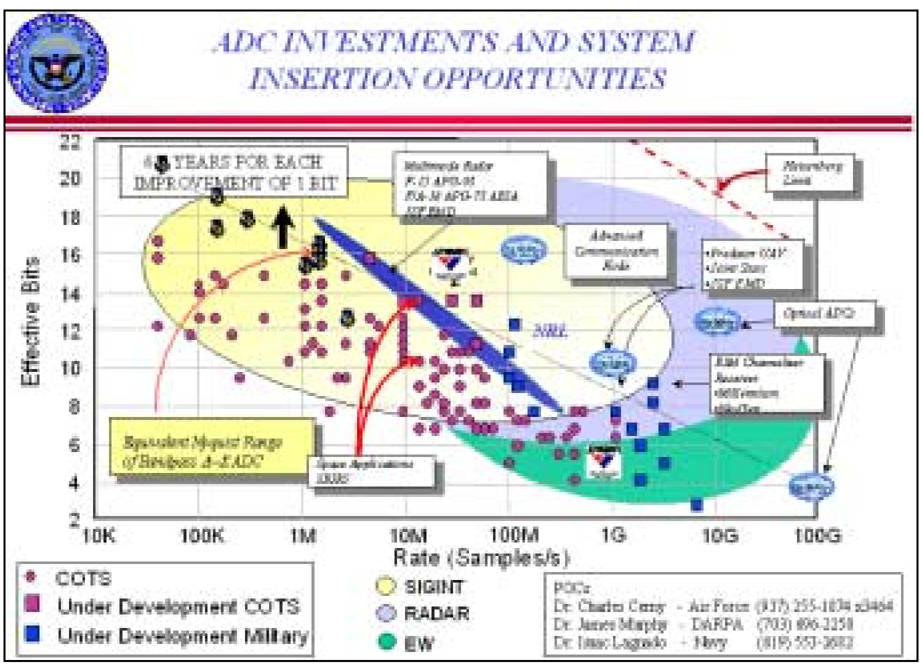


Figure 14. Achieved Analog-to-Digital Converter Results and Goals

Figure 15 and Figure 16 show some promising analog-to-digital converter designs recently developed by Lockheed Martin and Raytheon. If these circuits can be successfully fabricated, they may lead to a breakthrough in digital receiver performance.

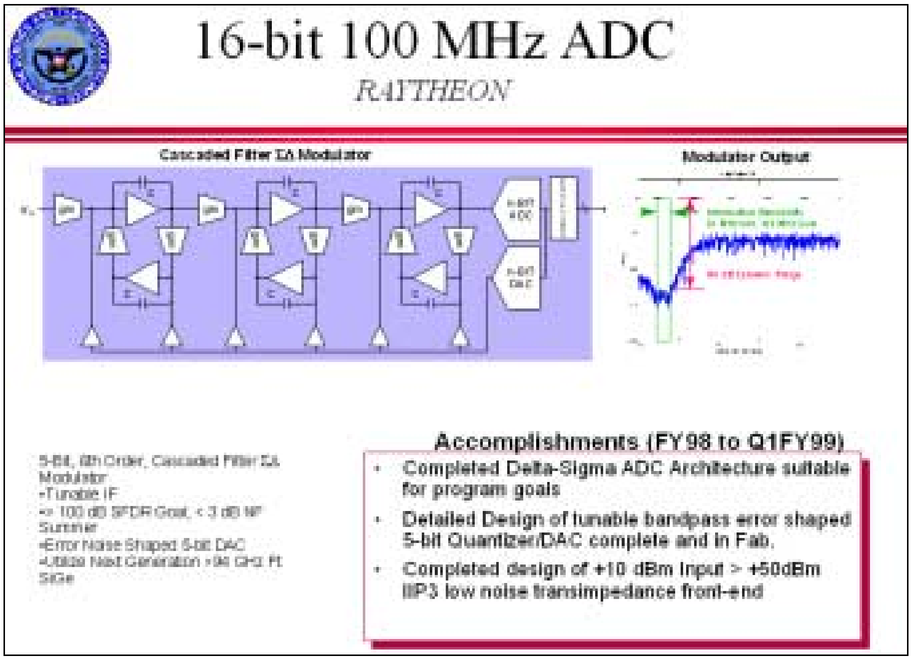


Figure 15. Raytheon 16-bit, 100 MHz ADC Design

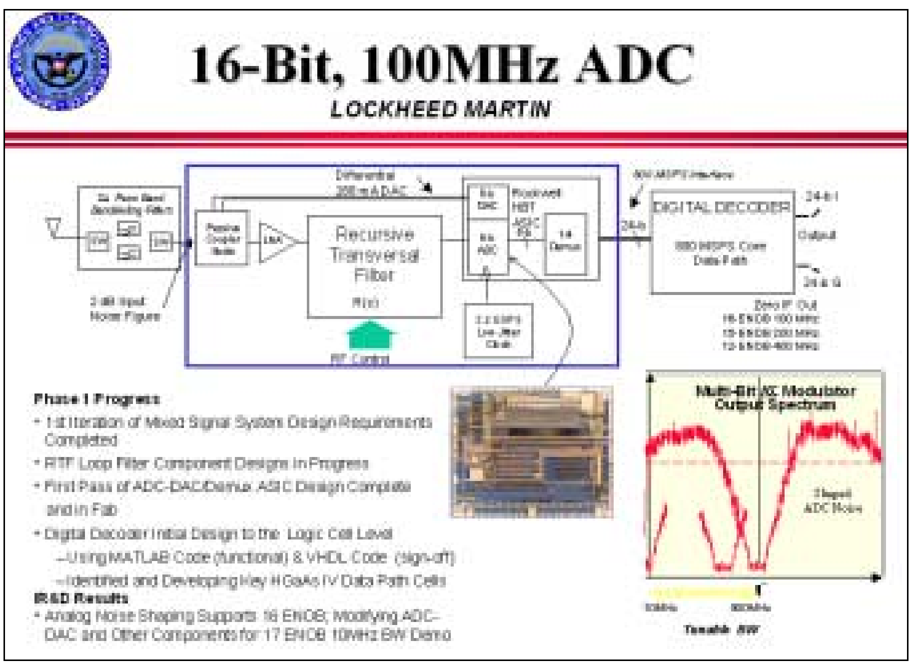


Figure 16. Lockheed Martin 16-bit, 100 MHz ADC Design

2.2.2 Radiation Hardened Electronics

Many types of vital DoD systems require radiation hardened electronics. These include missile interceptors, satellite systems, strategic missiles and nuclear weapons. Numerous studies have convincingly demonstrated that commercial-off-the-shelf (COTS) microelectronics falls far short of meeting the radiation hardness requirements for circuits that are used in systems such as those just mentioned (see Figure 17).

As a result, DoD has made significant investments over the years in the development of radiation hardened electronics that are suitable for meeting its system needs. The integrated circuits developed, in general, do not provide the performance characteristics available from current generation COTS integrated circuits; rather, the goal is to achieve adequate performance (i.e., performance similar to that of the last generation of COTS integrated circuits) while, at the same time, achieving the required levels of radiation tolerance. **Figure 18** shows some of the current device and circuit technology efforts and process and design technology efforts being pursued to meet high-density radiation resistant microelectronics requirements. Figure 19 is a summary of current (March 1999) and anticipated DoD customer requirements for radiation hardened electronics.

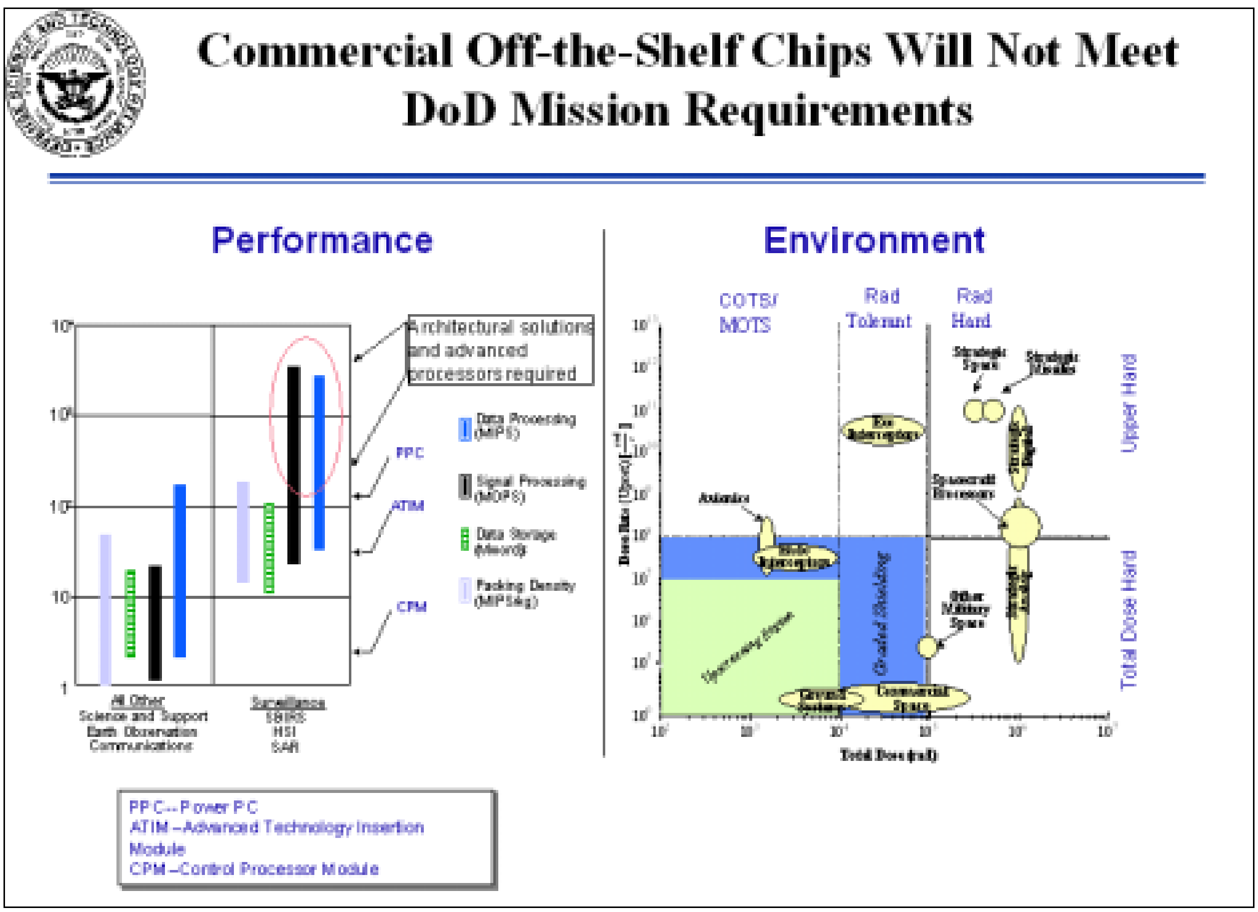


Figure 17. COTS Capabilities versus Military Requirements

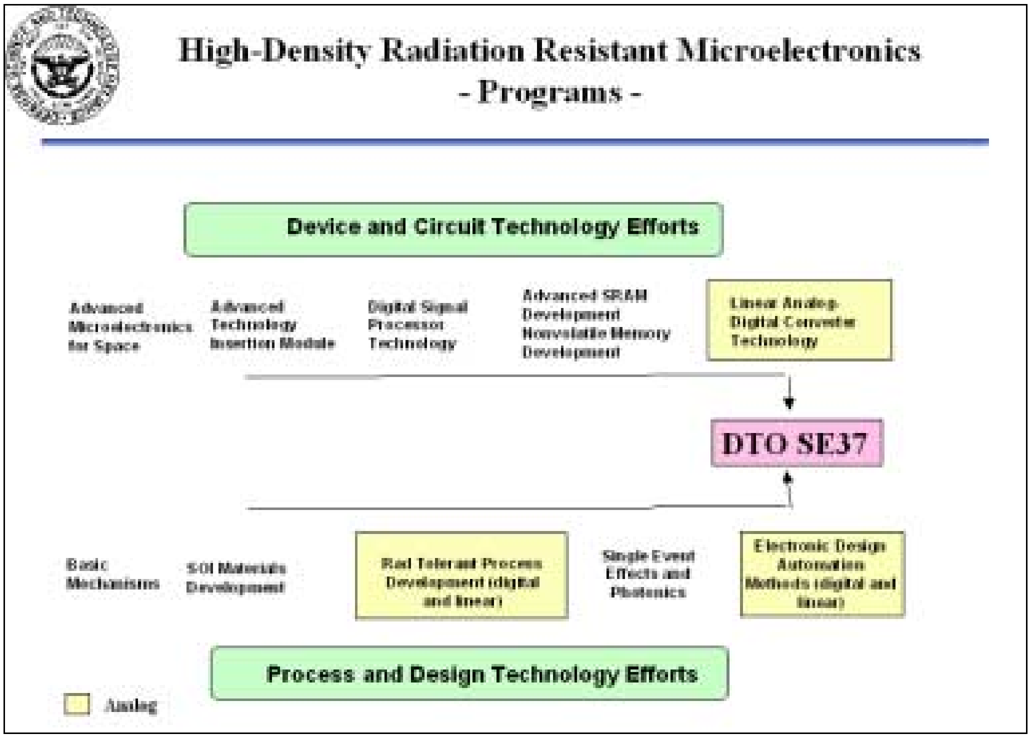


Figure 18. Current DoD High-Density Radiation Resistant Microelectronics Programs

Customer Needs Determine Program Focus

Customer	Date Needed	RH Product/Service
SBIRS-Low/High	01-03	1M SRAM and 4M SRAM 200 MIPS Microprocessor Low Power Gate Array 1M Non-volatile RAM
MILSTAR Follow-on (Adv EHF)	01-03	4M SRAM, 100 MIPS Microprocessor Low Power Gate Array 1M & 4M Non-volatile RAM
Space Based Laser (SBL)	2010-15	16M SRAM, 20 MIPS Microprocessor 4/8M Gate Array
Space Base Radar (SBR)	2008	16M SRAM ,500 MIPS Microprocessor 4/8M Gate Array
AF GSP (Advanced Guidance)	01-05	RH Analog SOI microelectronics 4M SRAM
GPS IIF	99-03	1M SRAM Low Power Gate Array
Trident AF&F Program	03-05	1M SRAM Low Power Gate Array RH Analog SOI microelectronics
NASA New Millennium Program	Various start 00	RH Low Power microelectronics

Figure 19. DoD Customer Requirements for Radiation Hardened Microelectronics (presented at 1999 TARA)

2.2.3 Micro-Electro-Mechanical Systems (MEMS)

These miniature sensors and actuators are expected, in conjunction with integrated circuits and photonic devices, to result in entire new generations of system capabilities for both military and commercial use. Because of the perceived importance of this technology, DARPA has devoted a major portion of its electronics science and technology (S&T) budget to its development. Funding for MEMS technology represented approximately one-sixth of the overall 1999 DoD electronics S&T budget. Figure 20 shows the planned allocation of MEMS funding during the next fiscal year, and Figure 21 shows some recent accomplishments resulting from DoD sponsored MEMS programs.

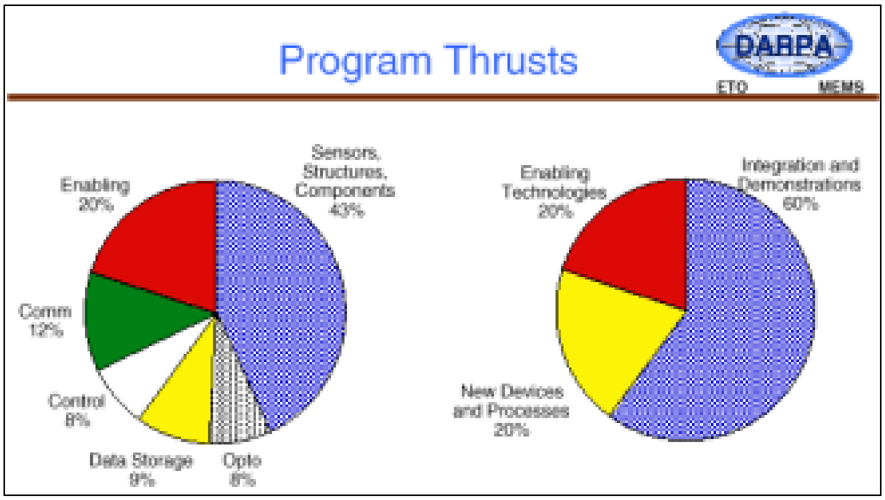


Figure 20. MEMS Program Thrusts

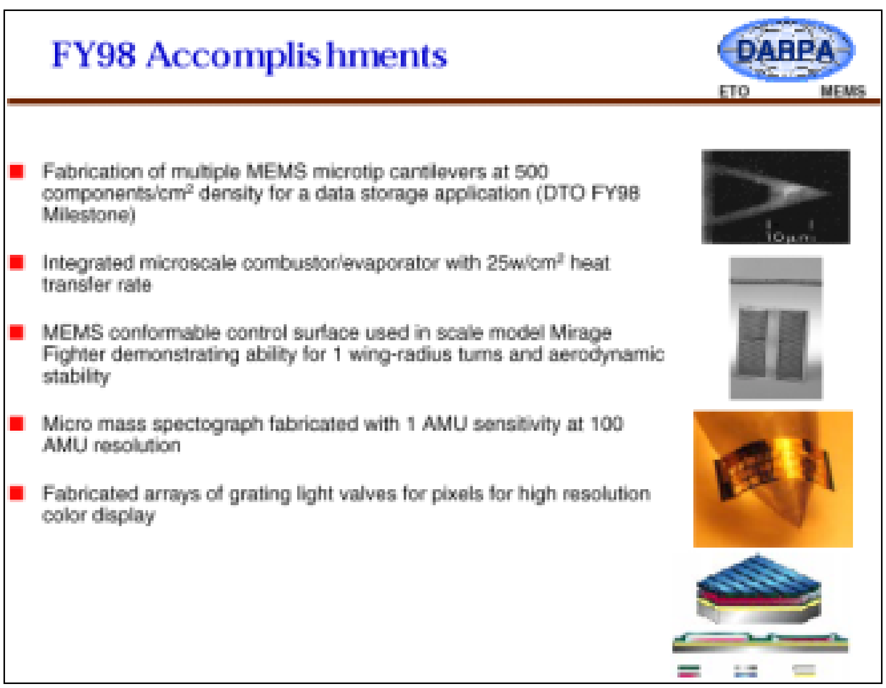


Figure 21. Recent MEMS Accomplishments

An exciting future application of MEMS is the generation of power using extremely tiny electro-thermal-chemical systems. Figure 22 shows a MEMS design under investigation for power generation.

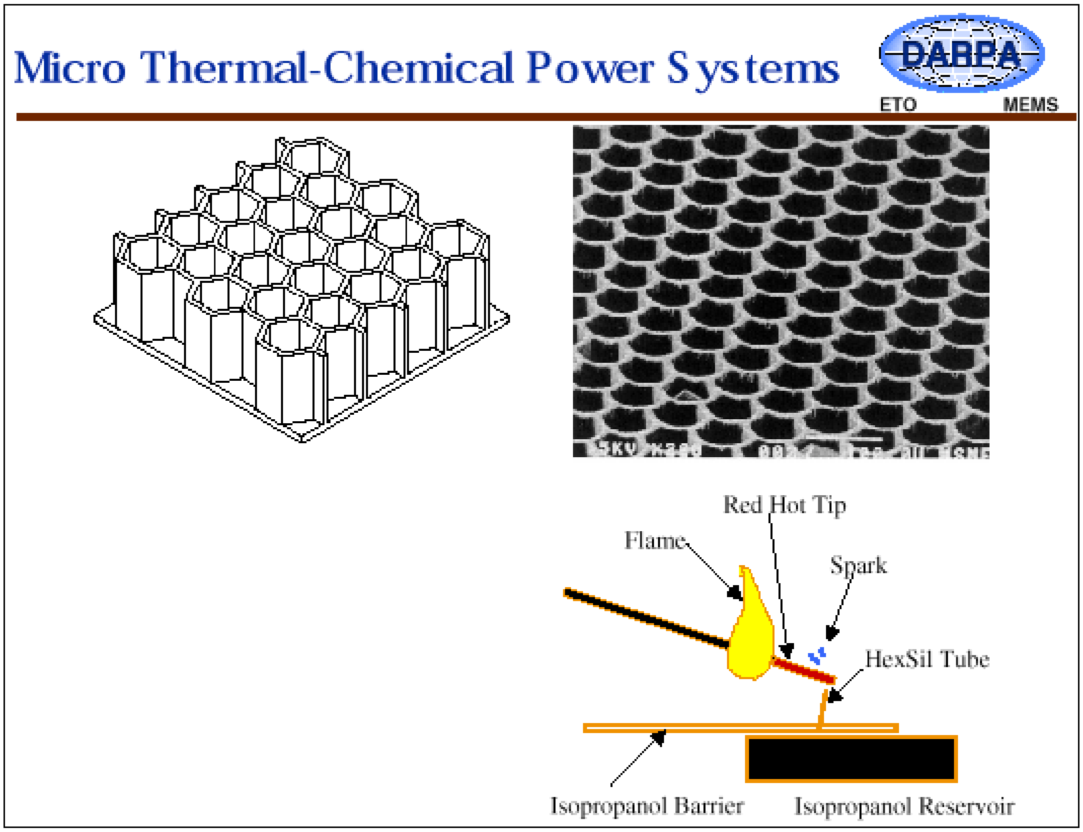


Figure 22. MEMS-Based Electro-Thermal-Chemical Power Systems

Combinations of MEMS sensors and actuators can perform a multiplicity of functions, with extremely low power requirements and occupying extremely small space. This is particularly valuable on platforms such as aircraft, satellites, and unmanned air vehicles. Figure 23 shows a design under development for integrated MEMS sensors and actuators, while Figure 24 illustrates some of the potential applications for these types of integrated MEMS components.

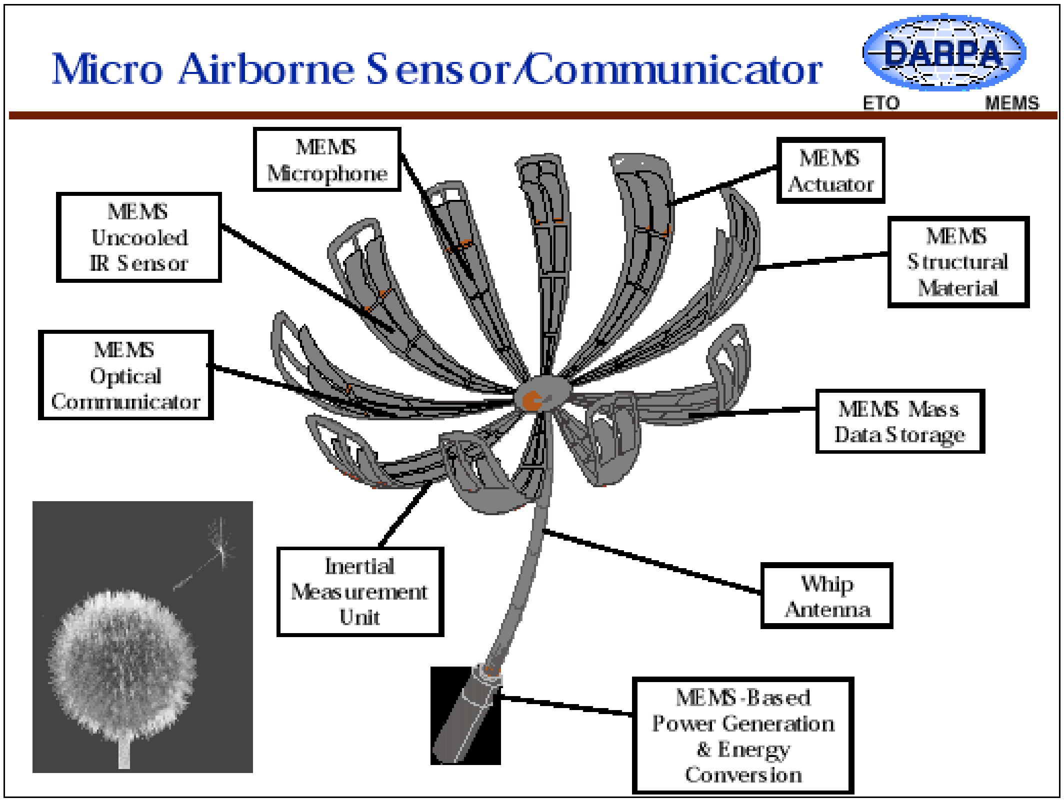


Figure 23. MEMS-Based Micro Airborne Sensor/Communicator

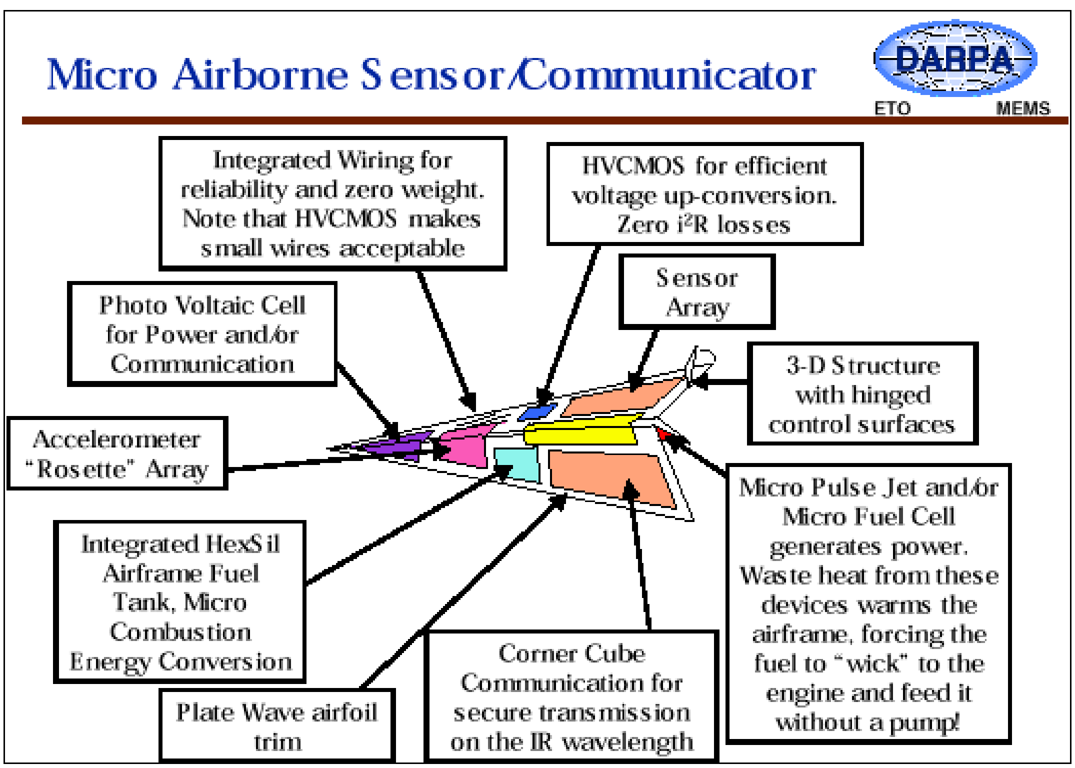


Figure 24. Potential Applications for MEMS Actuators and Sensors

2.2.4 *Sonoelectronics*

A recently initiated DARPA program seeks to develop advanced electronic devices that can detect hazardous objects, such as mines, under water. The systems under development can be characterized as compact underwater imaging systems that provide good resolution even in turbid water. They make use of both MEMS and MOS-based integrated circuits. Significant accomplishments have already been achieved as depicted in Figure 25 and Figure 26.

Figure 25. Lockheed Martin SonoCam

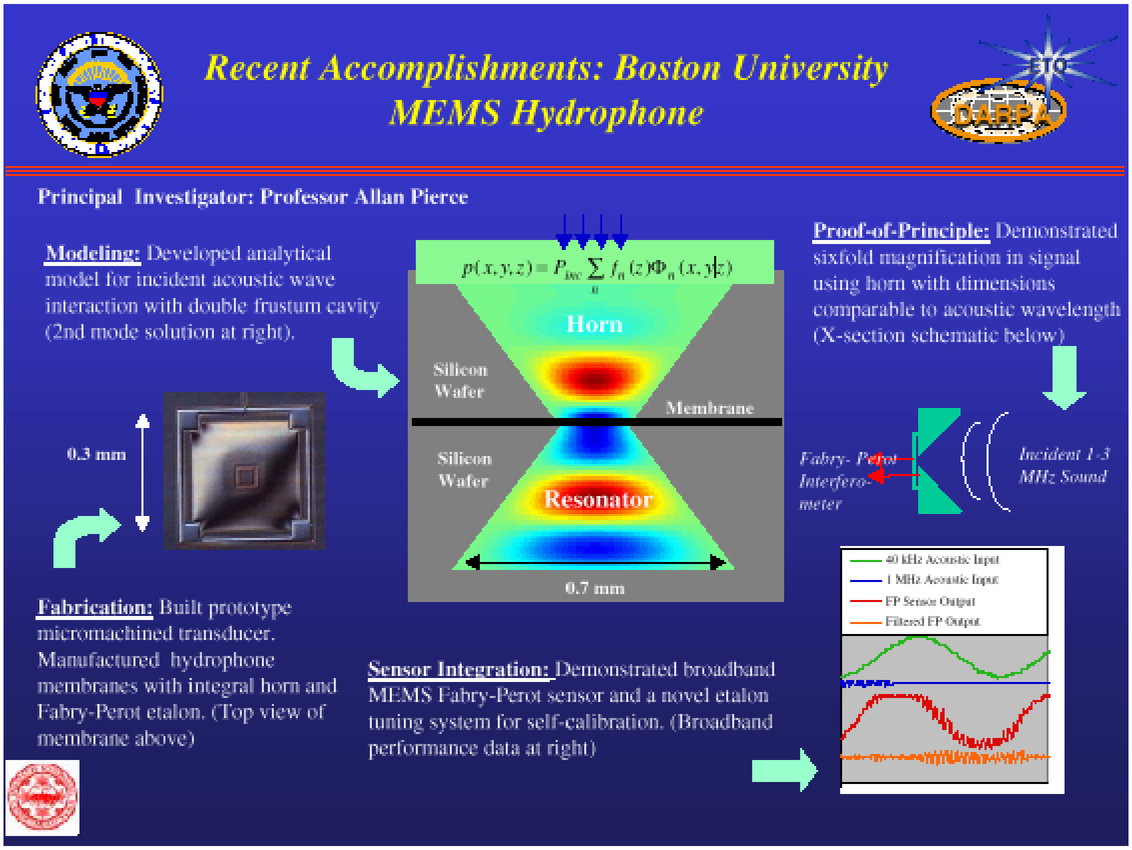


Figure 26. Boston University MEMS Hydrophone

2.2.5 High Power Solid State Electronics

DARPA, in conjunction with the Navy's Power Electronic Building Block (PEBB) program, is sponsoring a research program for the development of devices such as switches that can handle large amounts of current and voltage. These devices principally make use of wide-bandgap materials such as silicon carbide (SiC) or gallium nitride (GaN). Figure 27 shows some of their intended applications.

Significant work remains to be done to realize wide bandgap materials on wafers of sufficiently large size and in sufficient quantities to fabricate these switches in large enough quantities and at a low enough price to allow their use in systems. Some of the remaining material problems are summarized in Figure 28.

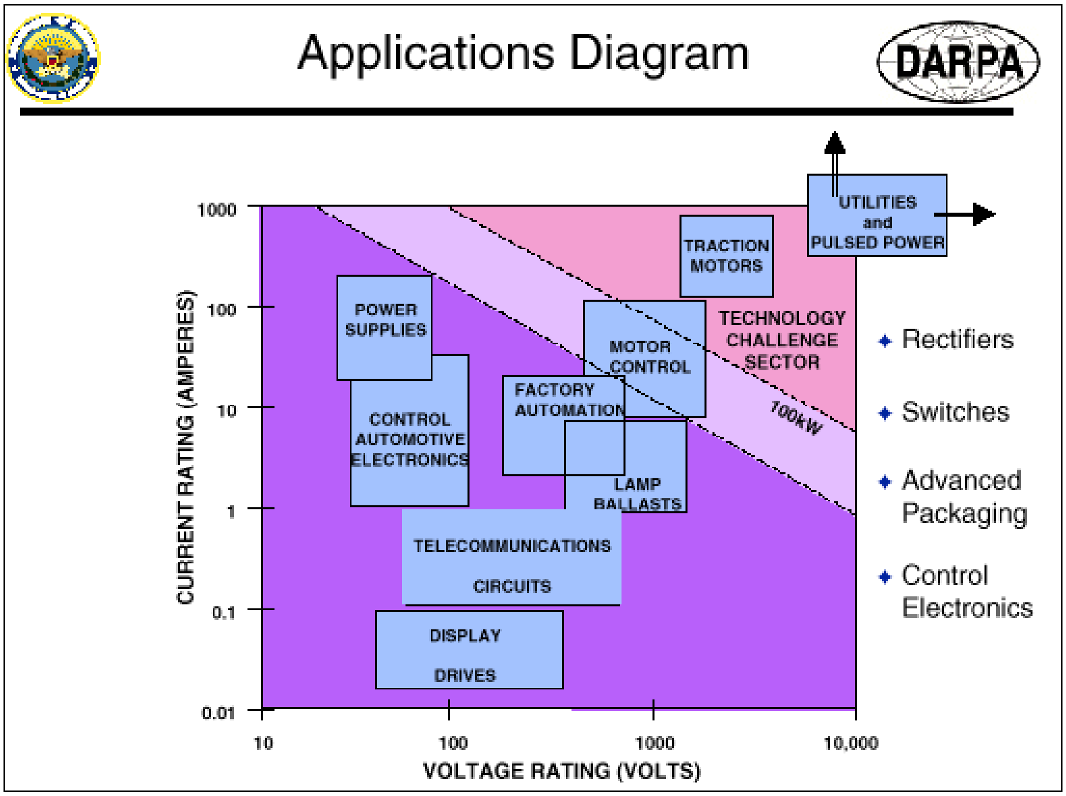


Figure 27. Potential Applications for Wide Bandgap, High Power Solid State Electronics

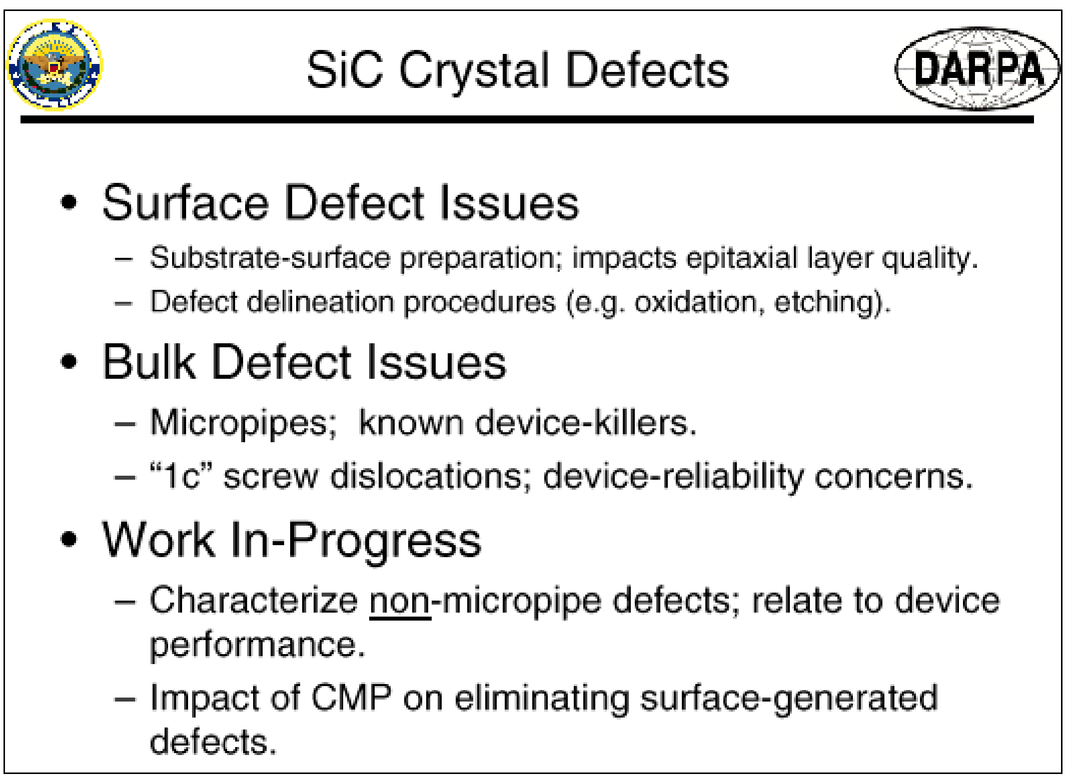


Figure 28. SiC Crystal Defects

2.2.6 Advanced Microelectronics

Development of integrated circuits with minimum feature sizes of less than 0.1µm will allow performance advances as well as power savings well beyond the current state-of-the-art. A DARPA nanoelectronics program is aimed at solving the numerous technology problems that must be overcome in order to make integrated circuits with 25 nanometer minimum feature sizes a reality. Achieving these circuits would allow development of a fast Fourier transform (FFT) chip for 1000 x 1000 picture elements and 32-bit resolution in a space of only a few square millimeters. It would also allow ultradense integrated circuits to be built directly onto the skin of micro-air vehicles. Figure 29 shows the objectives, approach and progress made during the past year on DARPA's 3-D integration program.

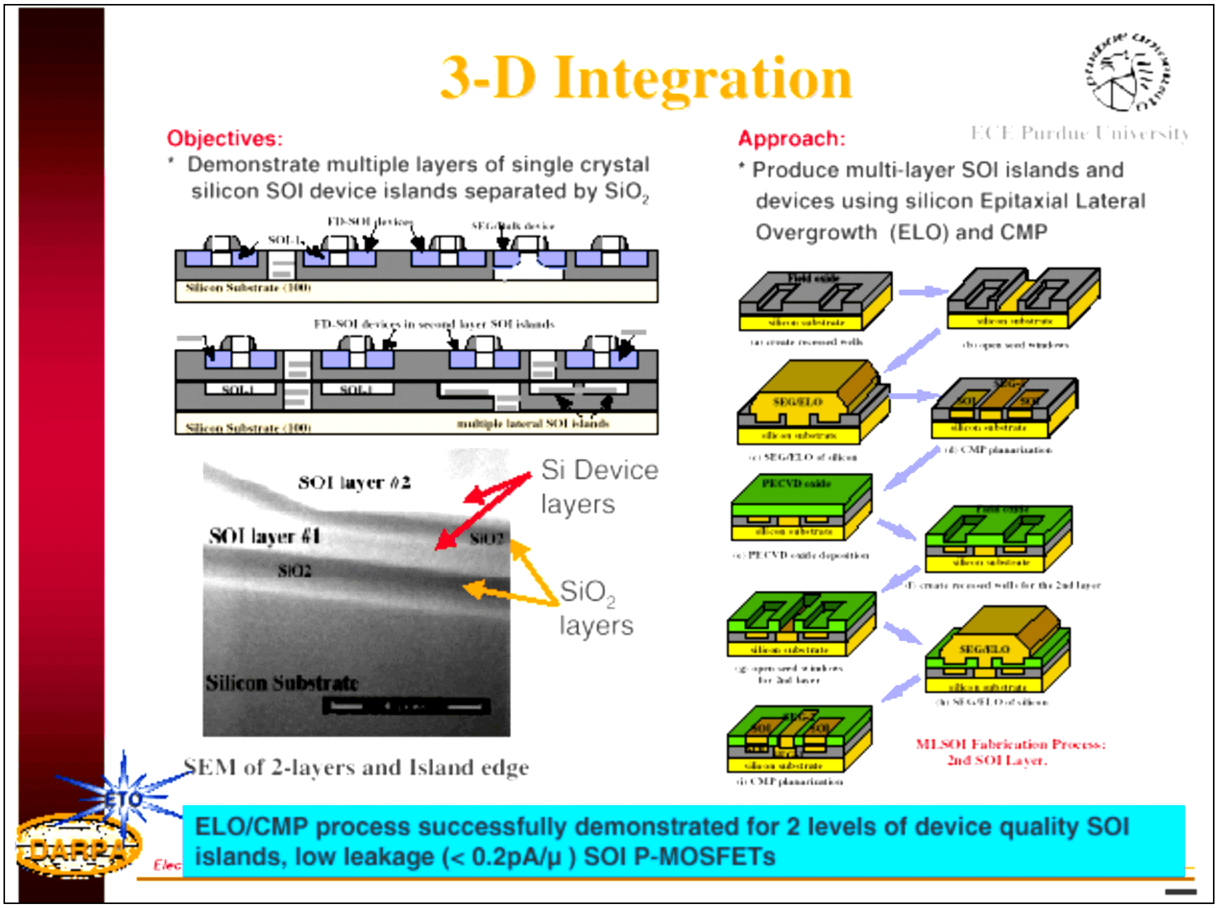


Figure 29. DARPA's 3-D Integration Program

2.3 Electro-Optics

2.3.1 Laser Technology

There are strong and well-coordinated S&T efforts funded by the Office of Naval Research for mid-IR diode lasers and high power fiber lasers. In addition, the recently held Infrared Countermeasures (IRCM) STAR recommended a new Defense Technology Objective

(DTO) be established for the development of high power lasers and for supporting S&T activities in electronics.

Nonlinear optical (NLO) materials enable new laser systems by providing a means for efficiently generating moderately-high power laser light at wavelengths where it has not been previously possible to do so and by providing laser light that is wavelength (frequency) tunable. NLO materials development is primarily accomplished by the Air Force Research Laboratory, Materials and Manufacturing Directorate. It is coordinated with a smaller effort at the Naval Air Warfare Center Aircraft Division. The efforts are well integrated with those of laser device and system developers, especially work on laser-based infrared countermeasures and chemical/biological warfare agent detection. The most important achievement during the past year has been the completion of the initial development of $ZnGeP_2$. This has enabled the generation of more than 20 watts of continuous power (OPO) in the mid-infrared region with high efficiency. $ZnGeP_2$ has been credited with enabling a number of device and system advances including the successful completion of the "DARPA/Tri-Service Mid-IR Laser Program." Ongoing efforts are focused upon developing NLO materials (both birefringent and periodically-poled crystals) for the spectral region from the UV through the far-IR. Special emphasis has been placed first upon new materials for the far-infrared region (8-12 microns) and second upon achieving dramatically improved energy per pulse generation across the entire mid- and far-infrared spectral regions.

2.3.2 Focal Plane Arrays

Uncooled focal plane arrays have progressed to a point where their performance is competitive with cooled arrays for many applications. Uncooled FPA producibility has been significantly enhanced – to the point where this technology is beginning to create some real civilian interest. It is expected that the economies of scale resulting from widened civilian use of this technology will lead to reduced acquisition cost for future DoD procurements.

In concert with advances with IRFPA sensors, significant advances are also being made in the development of integrated signal processors that allow significant enhancements of the "raw" detected color images. Figure 31 depicts some of the recent progress with these signal processors.

Focal plane array technology is becoming relatively mature with numerous applications, both military and commercial. Technology development is now entering its third generation. Figure 32 shows the 3^{rd} generation array technology goals for various types of IRFPAs.

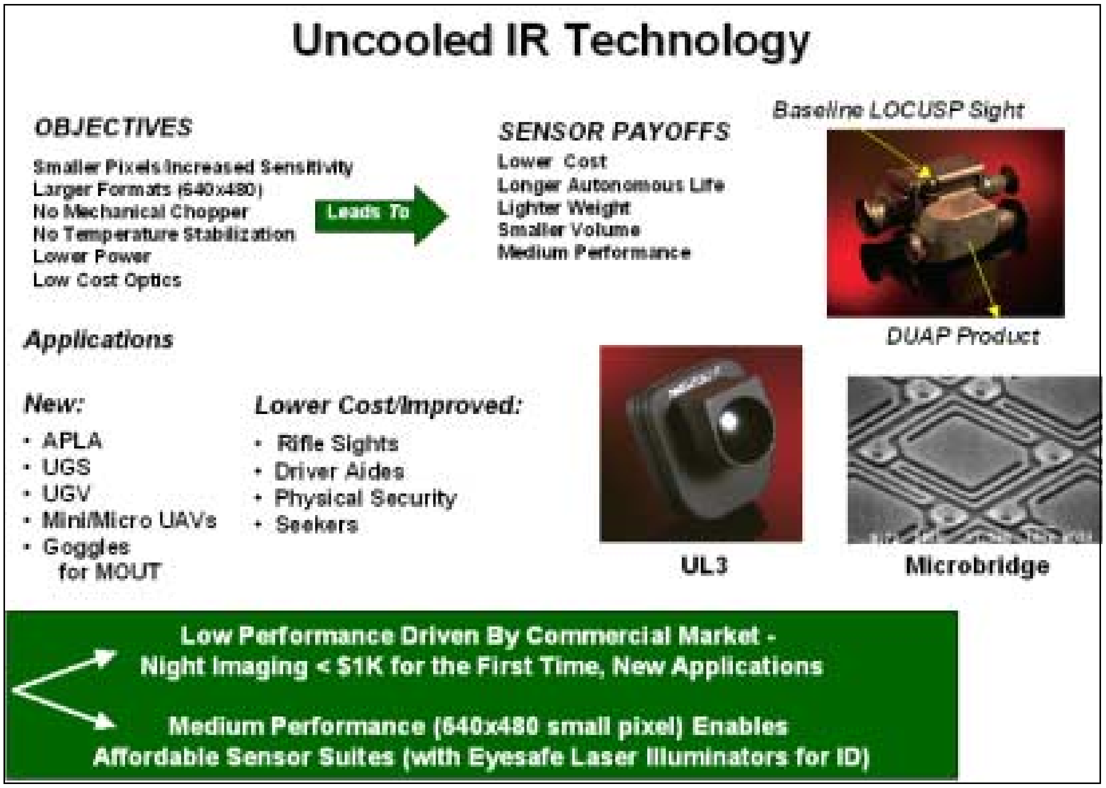


Figure 30. Uncooled IR Technology

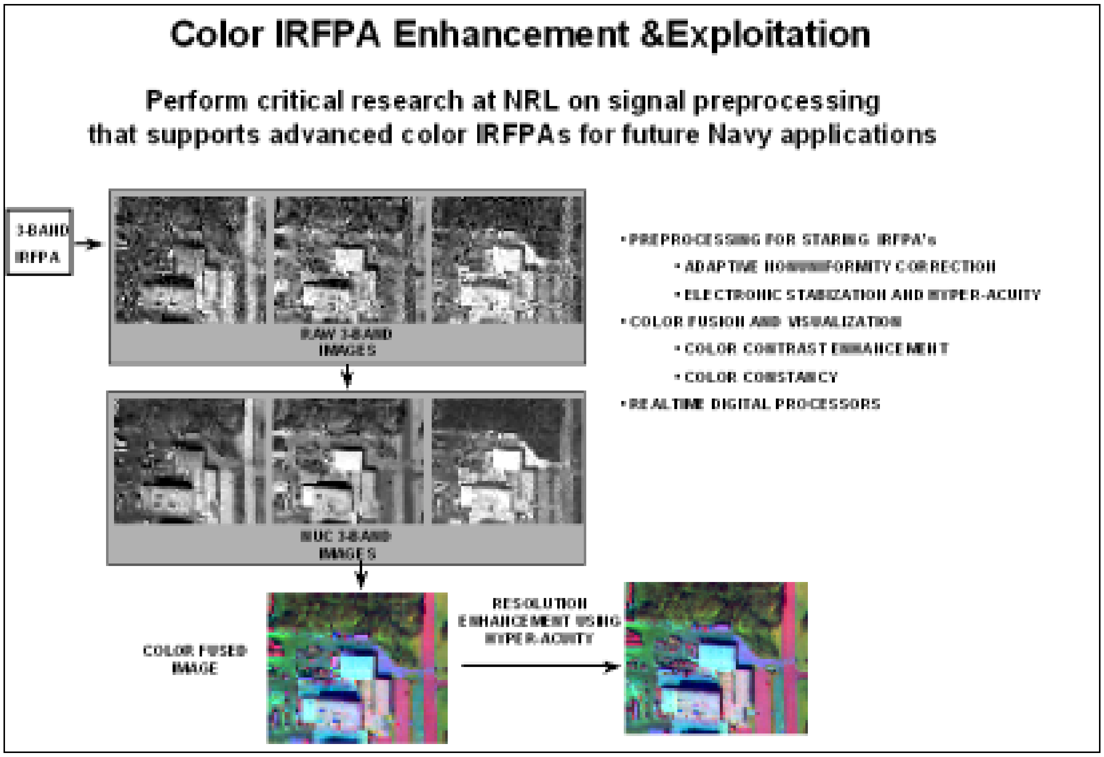


Figure 31. Color IRFPA Enhancement and Exploitation

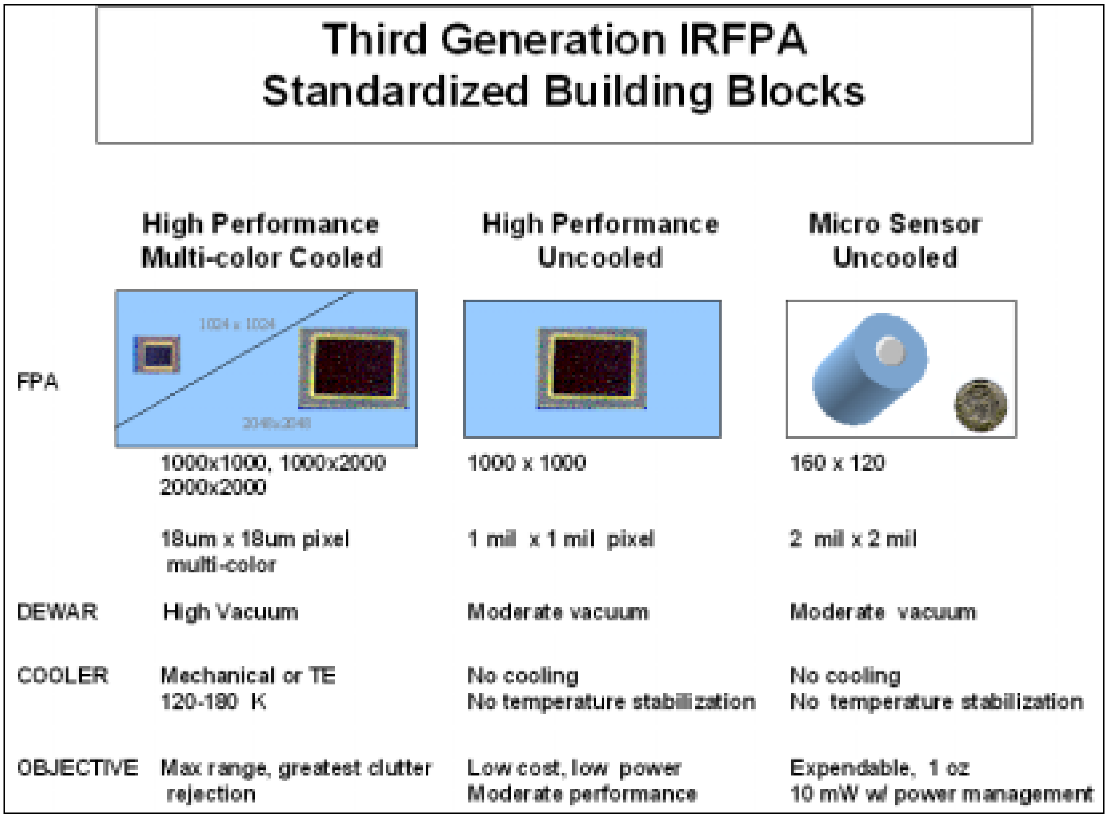


Figure 32. Third Generation IRFPA Technology Goals

2.3.3 Display Components

Rapid advances continue to be made in the development of high-resolution flat panel displays. Figure 33 illustrates some of the performance levels already achieved and the anticipated ones for this technology area over the next few years.

An important application for these displays is in aircraft and helicopter cockpits, as replacements for cathode ray tube displays. Figure 34 below shows the testing and demonstration at AFRL of a large flat panel display that utilizes digital micromirror devices (originally developed under DARPA funding). The intended use is in the AFRL Panoramic Crewstation.

Miniature display technology for head mounted units is also advancing quickly. Figure 35 below shows an exciting planned application for miniature displays. Figure 36 shows some of the near-term goals for one of the most advanced types of miniature display technologies – active matrix organic light emitting diodes (AMOLEDs).

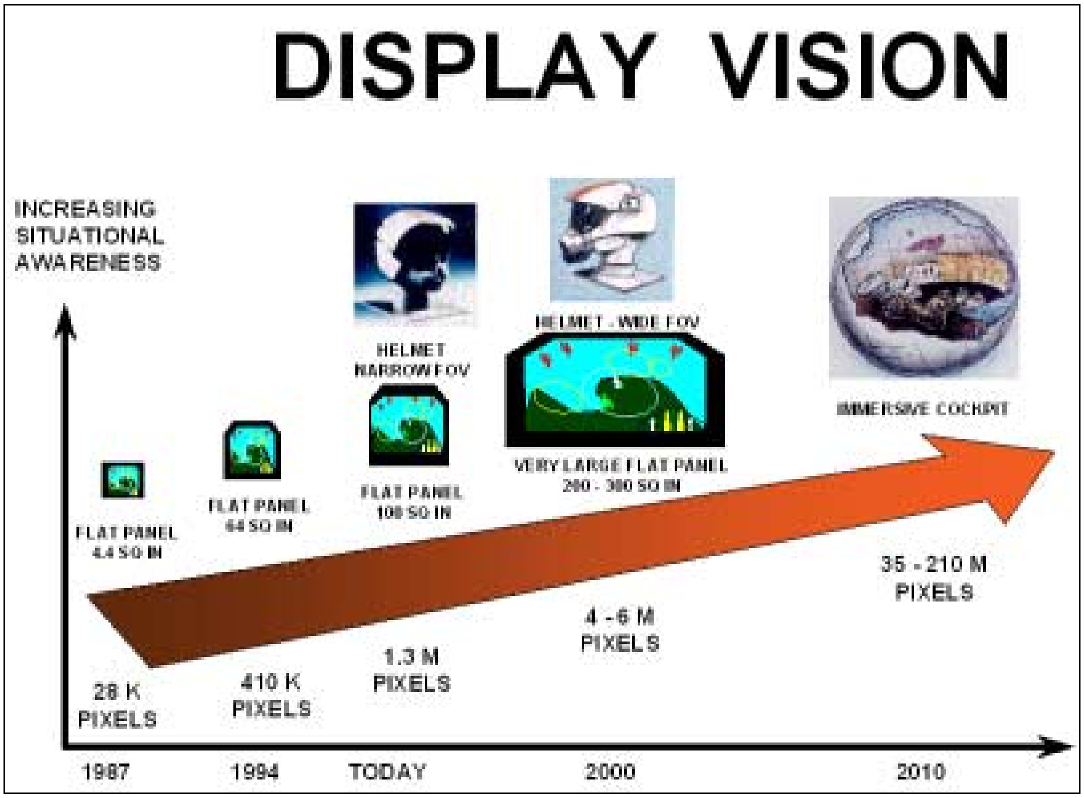


Figure 33. Progress in Flat Panel Displays

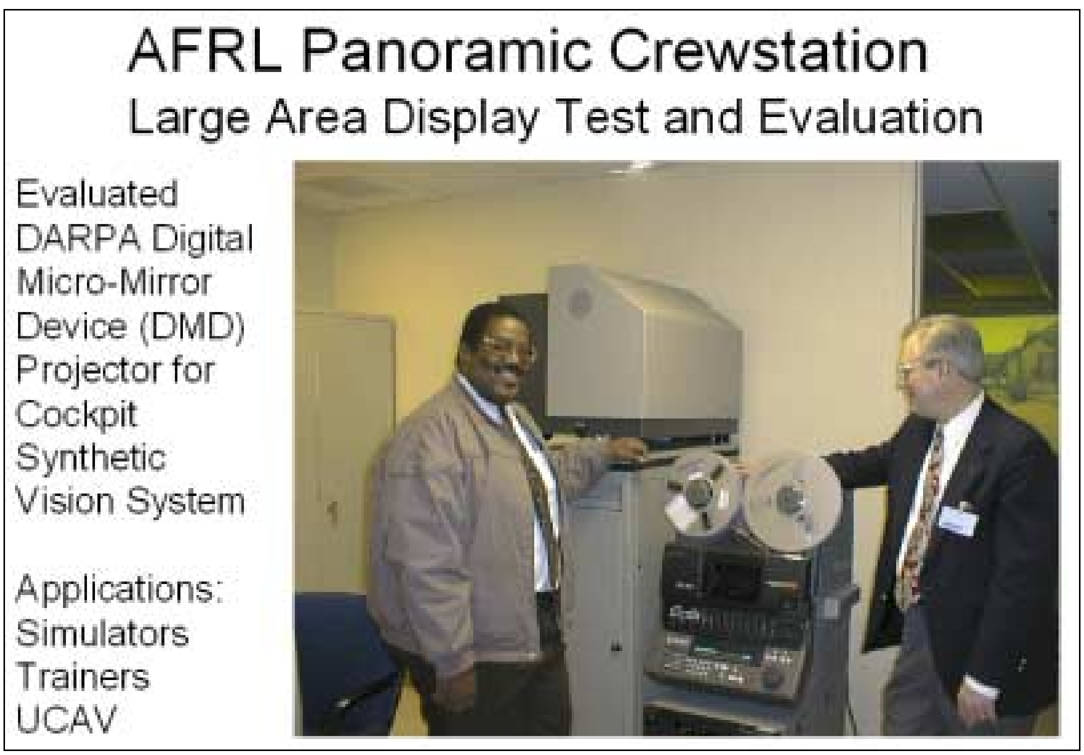


Figure 34. Flat Panel Display Demonstration and Test

Figure 35. Head Tracked Vision Systems

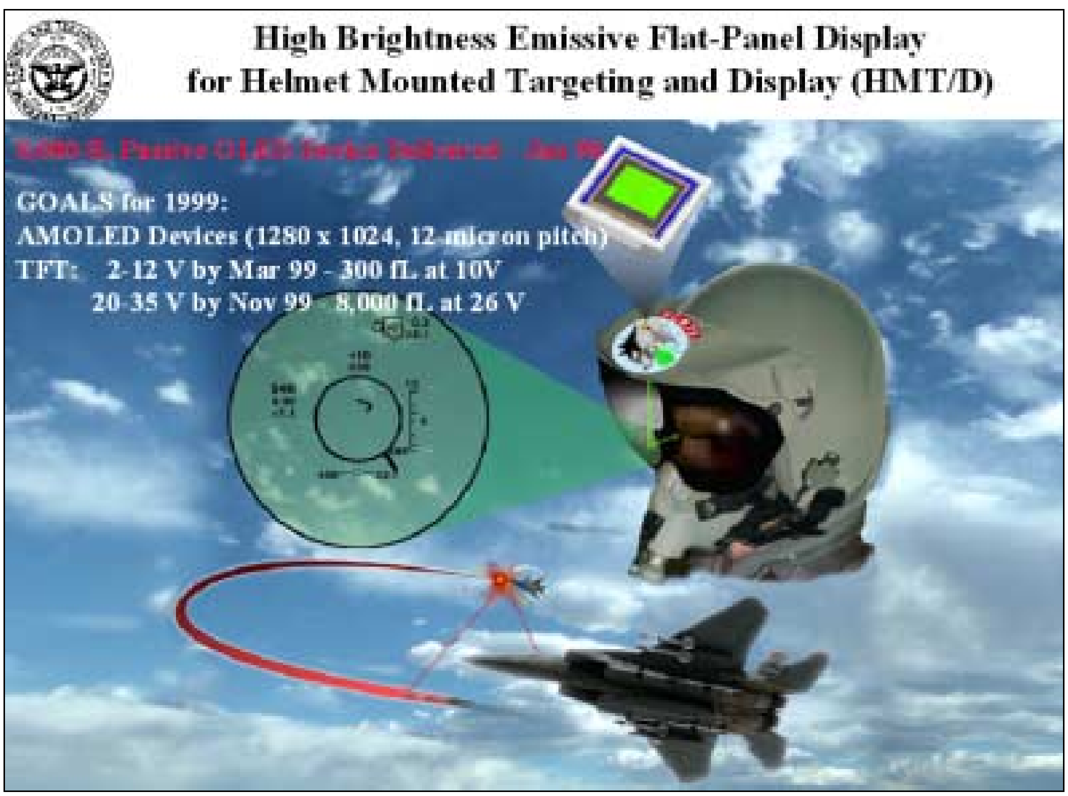


Figure 36. High-Brightness Emissive Flat Panel Display

2.3.4 Photonics/Fiber Optics

Photonic components offer the advantage of high-speed operation over much broader bandwidths than electronic components. It is likely that, in future systems, a combination of photonic and electronic circuitry will be used to take advantage of the best characteristics of both technologies. Figure 37 and Figure 38 below illustrate some of the recent advances in photonics achieved in-house at AFRL and, in other programs, under DARPA funding.

An additional use of photonics being actively investigated under DARPA and AFRL sponsorship is for analog-to-digital converters. Photonic converters offer the possibility of greatly enhanced resolution and sampling rates, including sampling directly at RF frequencies, as compared with electronic converters. However, many technical issues need to be resolved in order for these components to reach fruition. Figure 39 depicts a photonic ADC architecture currently under development.

Electro-optic (EO) polymeric materials are required to enable photonic technology used for optical communication between satellites and for advanced data-handling architectures on satellites and aircraft. These materials will enable the construction of high-frequency (exceeding 100GHz) optical modulators that operate at low voltages (V_{pi} as low as 0.1 volt) and with high tolerance to space radiation effects. EO polymer development is primarily accomplished by the Air Force Research Laboratory, Materials and Manufacturing Directorate and the Air Force Office of Scientific Research. Their work is coordinated with a smaller effort at the Naval Air Warfare Center at China Lake and with work sponsored by the Office of Naval Research. The most important achievements during the past year have been the demonstration of V_{pi} less than 1 volt and observation of initial evidence of the high radiation hardness of EO polymeric materials as compared with that of lithium niobate. A Dual-Use Science and Technology effort will begin soon to transition EO polymeric material technology to the commercial marketplace.

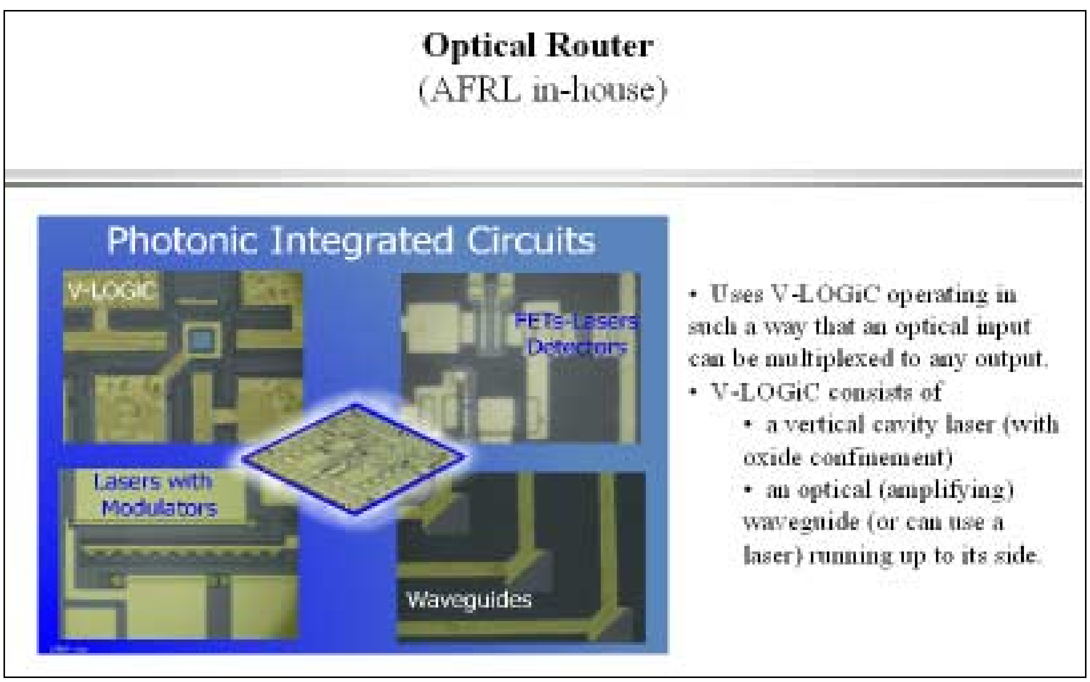


Figure 37. AFRL's Optical Router

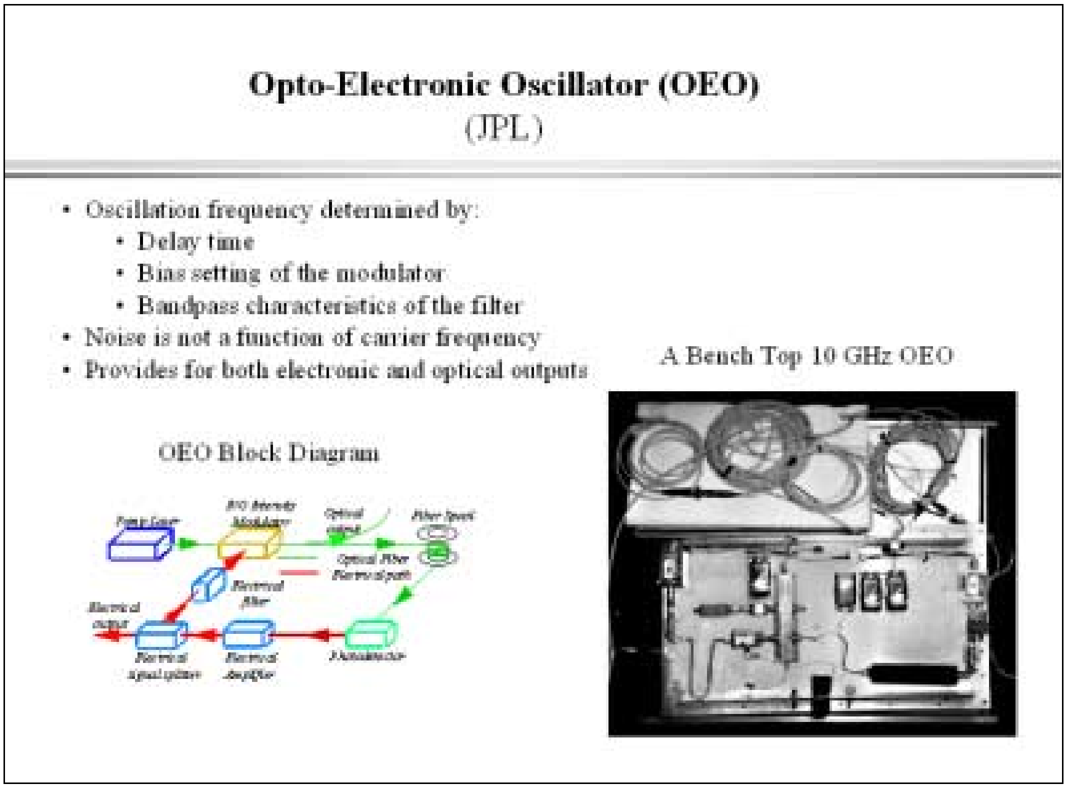


Figure 38. JPL's Opto-Electronic Oscillator

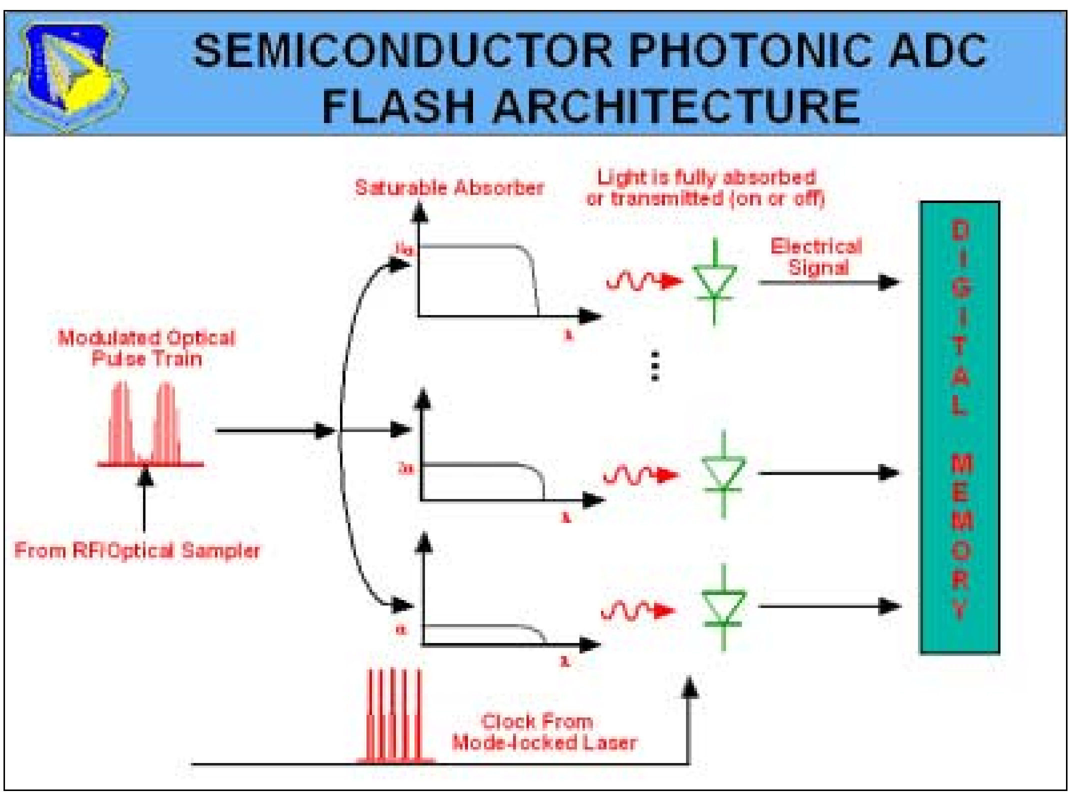


Figure 39. Developmental Semiconductor Photonic ADC Flash Architecture

2.4 Electronics Materials

High quality, low cost electronic materials are essential for achieving high performance electronic devices and integrated circuits. During the past several years, DoD S&T investment in electronics materials has been focused upon fabrication of wide bandgap materials, particularly silicon carbide and gallium nitride, with properties and wafer sizes suitable for use in producing high performance electronic devices. These wide bandgap materials allow devices to be built with high power densities and are suitable for operation at very high temperatures.

A smaller investment has been made in types of narrow bandgap semiconductor materials, sometimes called 6.1-Angstrom materials because of their crystalline lattice spacing. These latter semiconductors show promise for use in laser structures and possibly for low noise microwave and millimeter wave devices that can operate at very low voltages. Figure 40 and Figure 41 show examples of recent progress in wide bandgap materials technology made under DoD S&T funding.

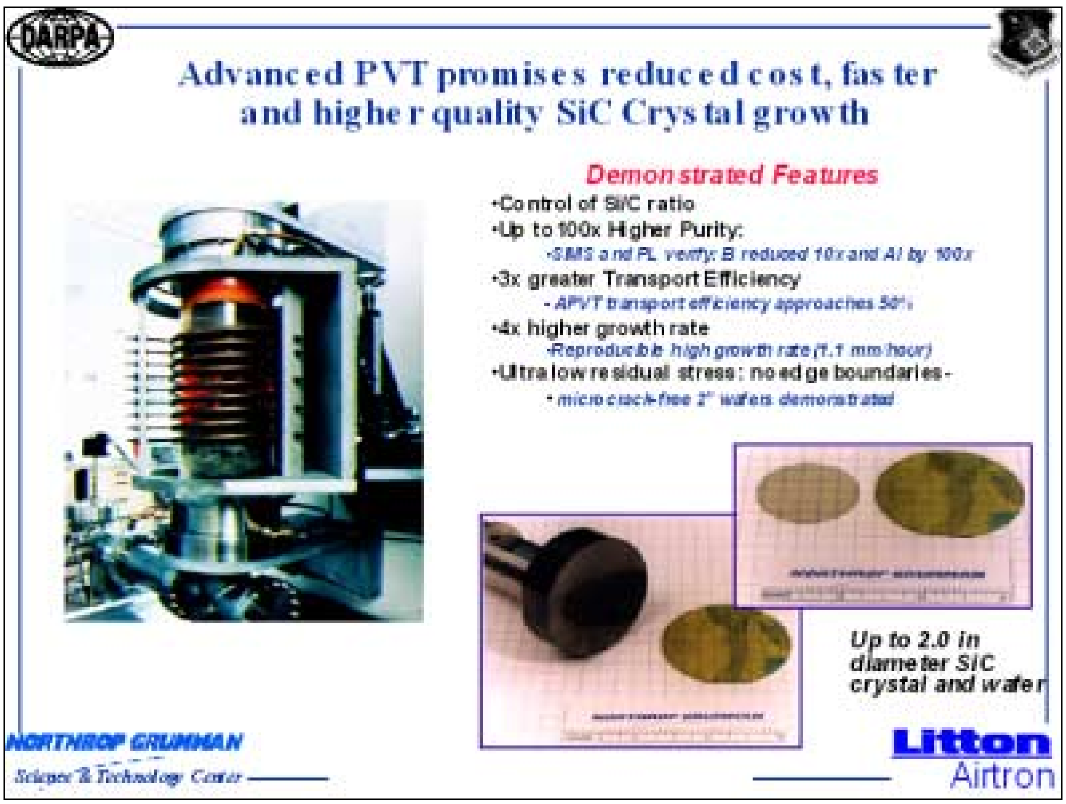


Figure 40. Progress in Silicon Carbide Material Growth

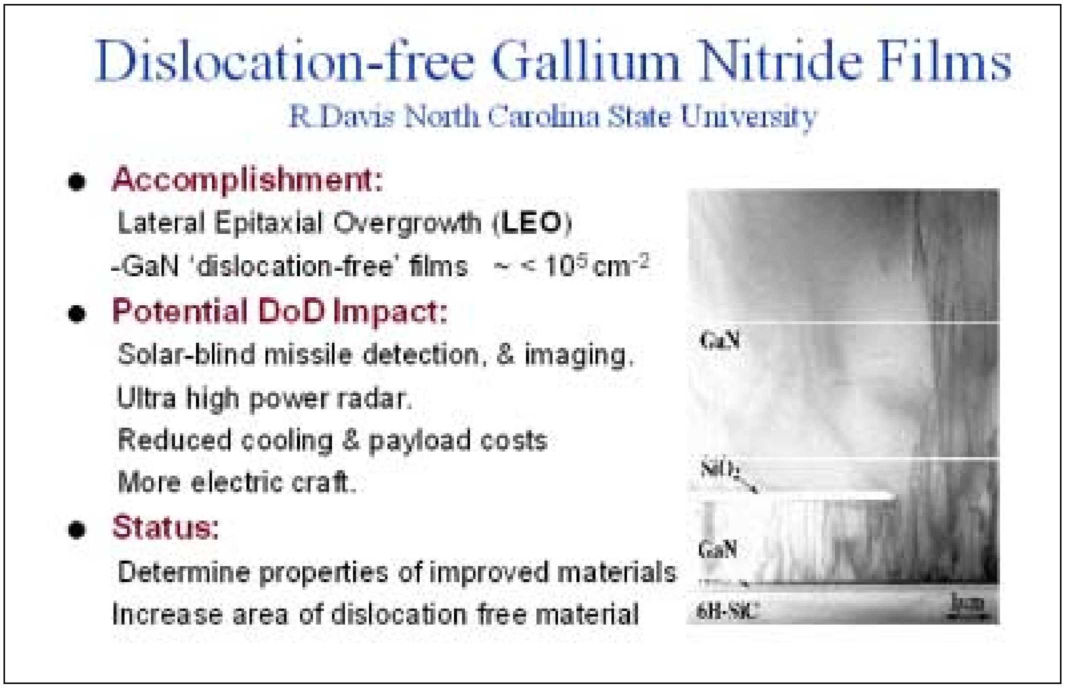


Figure 41. Dislocation-Free Gallium Nitride Films

2.5 Electronics Integration Technologies

In the DoD taxonomy, Electronics Integration Technologies (EIT) include, design, test and quality assurance, packaging, interconnect and assembly, energy storage and generation and distributed power. Little progress was made on test and quality assurance during the past year because of the almost complete lack of funding following the termination of the Air Force's reliability program. Representative achievements for each of the other Electronics Integration Technology areas are provided by the figures below.

2.5.1 Packaging Technology

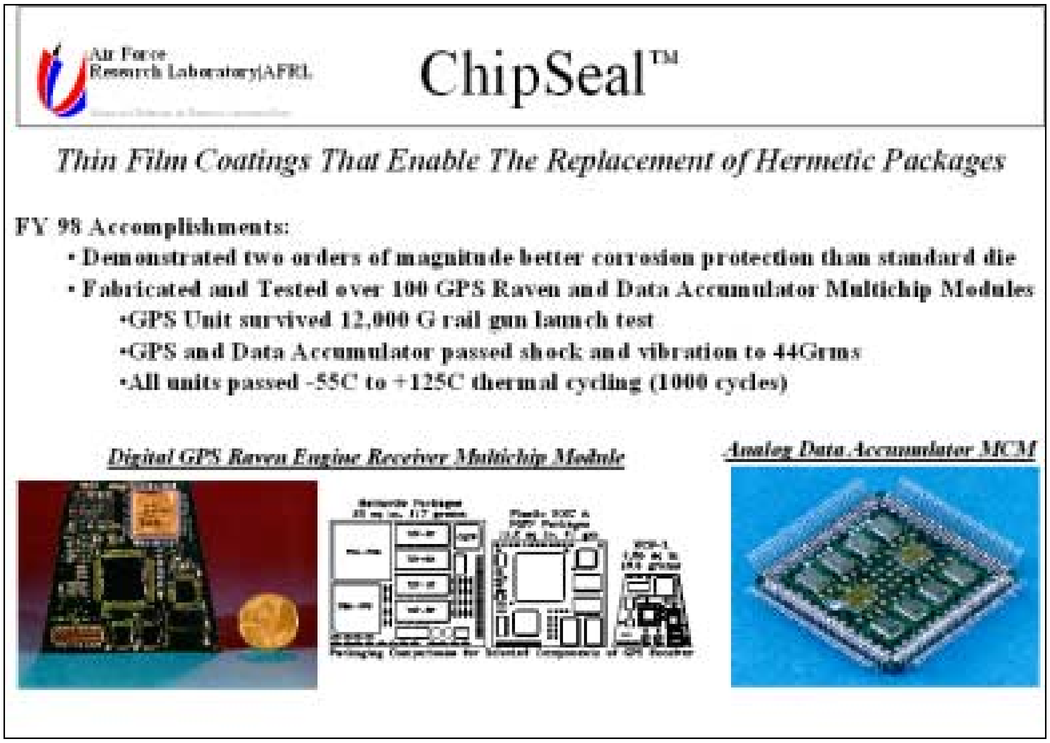


Figure 42. ChipSeal Packaging Technology

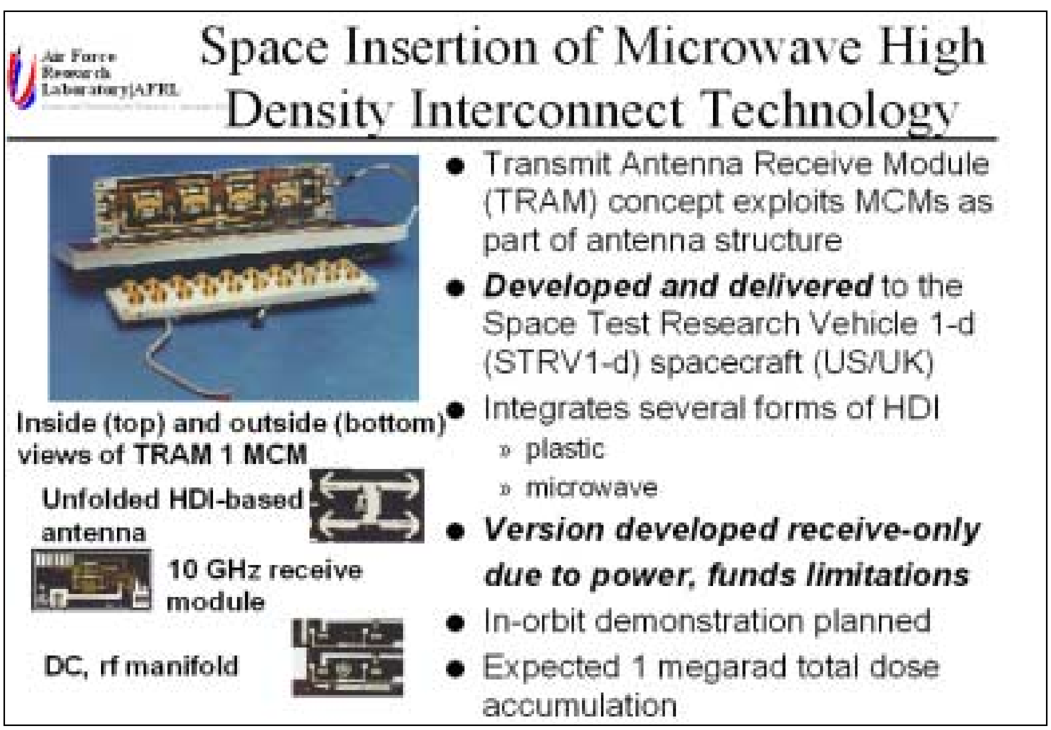


Figure 43. Space Insertion of High Density Interconnect Technology

2.5.2 *Integrated Design*

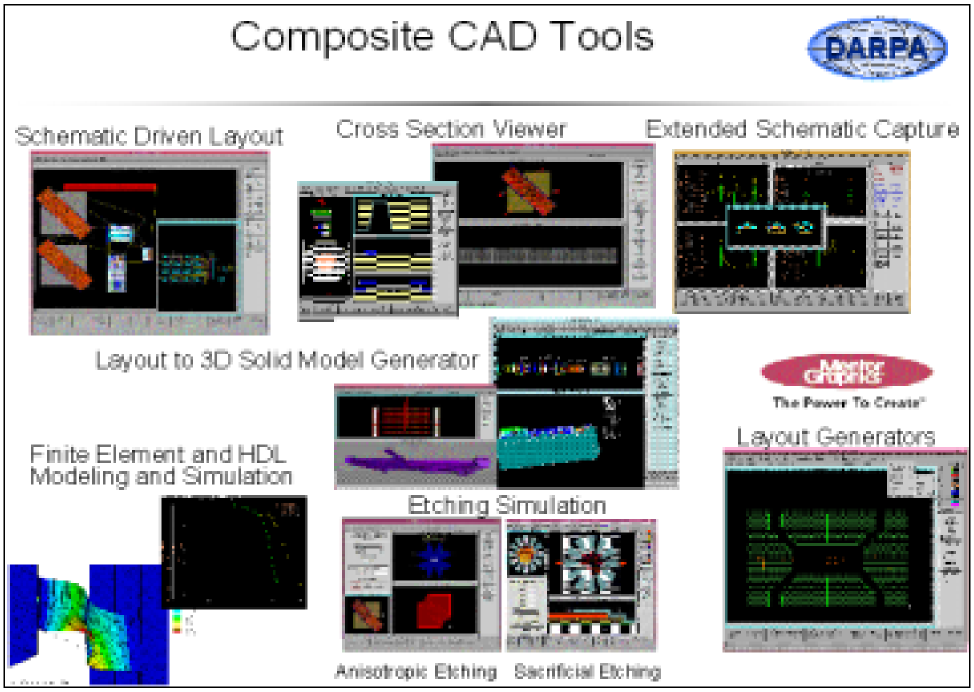


Figure 44. Composite CAD Integrated Design Tools

2.5.3 *Energy Storage and Generation*

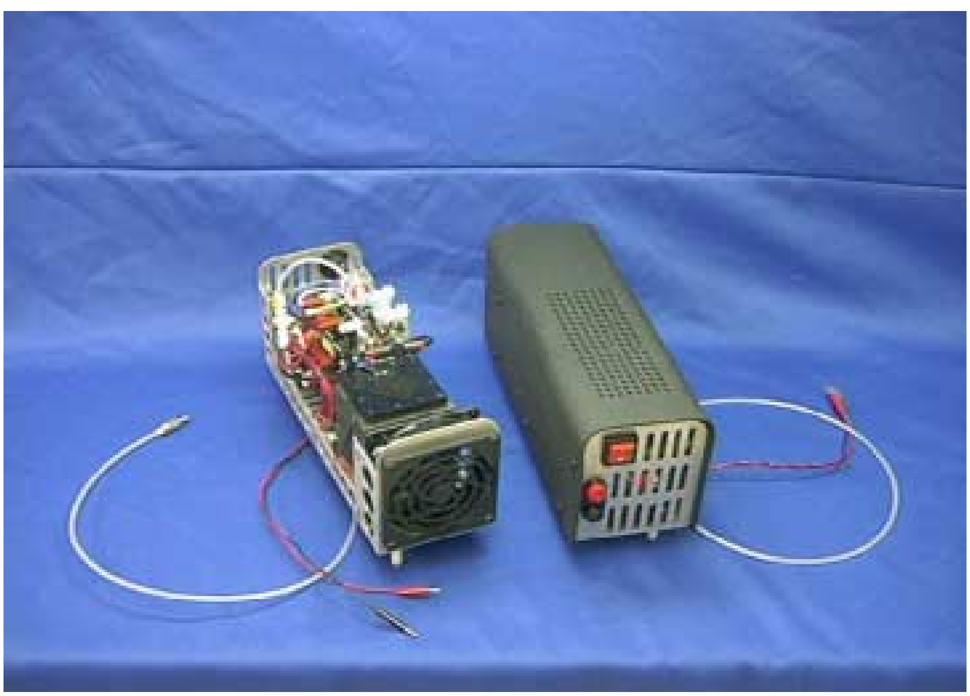


Figure 45. Lightweight 50-W PEM Fuel Cell Aimed at Supporting the Individual Soldier Portable Power Concept, Developed by U.S. Army CECOM and DARPA

2.5.4 Power Control and Distribution

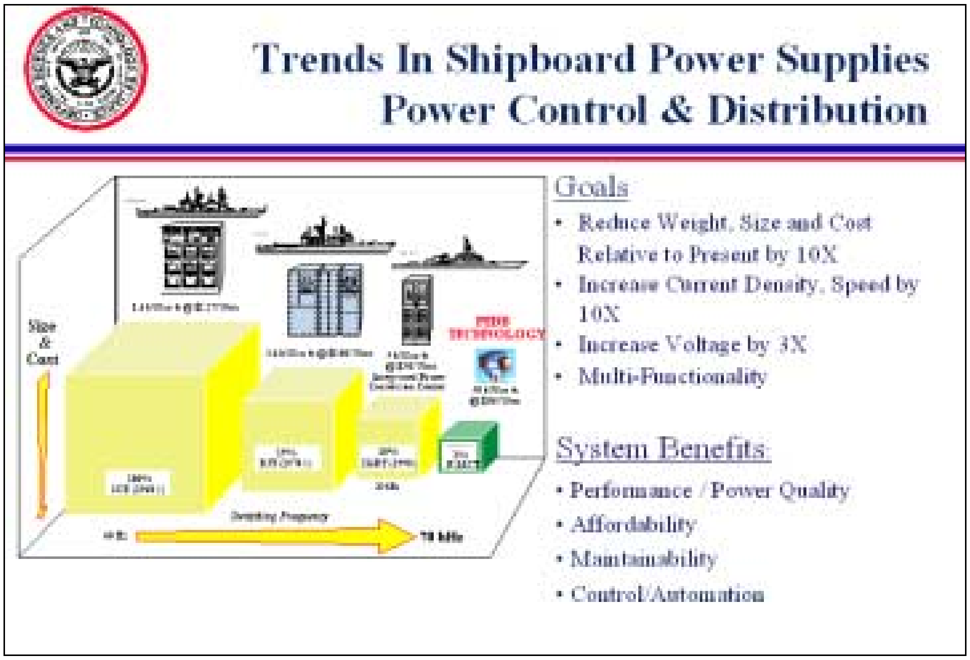


Figure 46. Trends in Shipboard Power Supplies

2.6 Significant Electron Device and Electronics Technology Developments Within the Past Year

During the past year, the following important technology advances have occurred. Some have been achieved under DoD funding; others are non DoD-funded results achieved by companies, organizations and universities throughout the world which may well serve the DoD as candidate technologies and infrastructure enhancements requiring additional development for future systems.

Microwave and Millimeter Wave Devices and Circuits

A noise figure of 0.9 dB with associated gain of 8.9 dB at 18 GHz was achieved using a 0.12-µm T-gate MESFET. F_t for the device was 121 GHz; f_{max} was 160 GHz. (University of Illinois) (*IEEE Electron Device Letters*, Vol. 20, No. 5, May 1999)

Many traditional GaAs MMIC suppliers are devoting a significant portion of their production capacity to producing silicon and silicon-germanium based RF ICs. These companies include RF Micro Devices, which is using IBM's silicon germanium process to produce RF ICs, and Anadigics and Triquint that are fabricating silicon RF ICs. In addition, Vitesse, a digital GaAs IC supplier, now has 60% of its designers working on CMOS products and has acquired three silicon-based companies during the past year. (*EE Times*, October 18, 1999)

Pseudomorphic InP HEMTs with Dry-Etched Source Vias Having 190 mW Output Power and 40% PAE at V-Band have been developed. Gate dimensions were 0.15µm x 500µm. (TRW) (*IEEE Electron Device Letters*, Vol. 20, No. 10, October 1999)

A 3-stage amplifier using metamorphic HEMTs (i.e., HEMTs with an InP active layer on a GaAs substrate) has achieved a noise figure of 4.2 dB with 18 dB associated gain at 82 GHz and a noise figure of 4.8 dB with 14 dB gain at 89 GHz. Device f_t was 225 GHz. (Sanders, a Lockheed Martin Company) (DARPA Sponsored) (*IEEE Electron Device Letters*, Vol. 20, No. 11, November 1999)

An extremely wideband six stage amplifier was built using an InP HEMT. It was the first single-chip amplifier operating above 140 GHz with sufficient gain to be useful. Its noise figure was 10.1 dB at 176 GHz when biased for highest gain and 8.1 dB noise figure at 176 GHz (with 7dB lower gain) when biased for lowest noise figure. Nominal gain was 20+/- 6dB over the band from 150 GHz to 215 GHz. (University of Massachusetts, JPL, TRW) (*IEEE Microwave and Guided Wave Letters*, Vol. 9, No. 7, July 1999)

A 4 mm wide GaN/AlGaN HEMT grown on SiC, has produced 11.7 watts of output power with 28% power added efficiency at 8.2 GHz. (Nitres) (http://www.nitres.com/Pages/nitres_tech_micro.html)

Power output of 6.3 watts has been obtained at 10 GHz from a 1-mm wide GaN/AlGaN MODFET grown on semi-insulating SiC. This is the highest output power density report for a 1mm or larger power device. (HRL Laboratories Press Release)

Wideband GaN HEMT amplifiers have been fabricated, one provides 1.6 watts of power output, the other provides 3.2 watts of power output over a major portion of the 3-9 GHz frequency band. Power added efficiency for these amplifiers ranged from 14% to 24% across their frequency band of operation. (Sponsored by ONR) (WiTech (now Nitres) and University of California, Santa Barbara) (*IEEE Microwave and Guided Wave Letters*, Vol. 9, No. 8, August 1999)

The first AlGaN/GaN HBT structure was reported. It had a current gain of 3. (Sponsored by ONR) (University of California, Santa Barbara) (*IEEE Electron Device Letters*, Vol. 20, No. 6, June 1999)

AlInAs/GaInAs HBT's with 0.4µm emitters and 0.4µm collectors have yielded 17.5 dB unilateral gain at 110 GHz. This result can be extrapolated to predict a power gain cutoff frequency, f_{max} of 820 GHz. (Sponsored by ONR) (University of California, Santa Barbara and JPL) (*IEEE Electron Device Letters*, Vol.20, No. 8, August 1999)

A superconducting hot-electron bolometer mixer receiver operating from 1 to 1.26 THz has been developed. It uses two solid-state local oscillators, each consisting of a Gunn oscillator followed by two stages of varactor frequency multiplication. One operates at a center frequency of 1 THz; the other at a center frequency of 1.26 THz. The tunable LOs provide only a few microwatts of output power, but are useful for implementing terahertz receivers. (Harvard-Smithsonian Center for Astrophysics, Cal Tech., Moscow State Pedagogical University) (*IEEE Microwave and Guided Wave Letters*, Vol. 9, No. 9, September 1999)

A SiGe MODFET with a 0.25-µm gate length has achieved a f_{max} of 120GHz and a f_t of 42 GHz. (Daimler Chrysler Research Center, University of Ulm) (*IEEE Microwave and Guided Wave Letters*, Vol. 9, No. 10, October 1999)

Packages and Interconnects

Masterslice™ technology is a 3-dimensional methodology for interconnecting MMICs with each other and with embedded passive components. Numerous successful demonstrations of Masterslice™ capabilities, using both silicon and gallium arsenide wafers, have been performed previously. This year a V-band amplifier with 8 dB gain and a 5.3 dB noise figure was implemented in an area of $0.27mm^2$. An image rejection mixer was also built with a conversion gain of –10 dB and an image rejection ratio of 20 dB. These performances can be compared with those of (much larger) conventional planar-formed MMICs. (NTT) (*IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 9, September 1999)

A Ka-band silicon package has been produced that can shield and electromagnetically isolate monolithic-microwave integrated circuit components. (Sponsored by Army Research Office and the Office of Naval Research) (Motorola and University of Michigan) (*IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 8, August 1999)

The first digital integrated circuits with copper interconnections and 0.18-µm minimum feature sizes are being shipped. The leaders, including IBM, UMC Group and Motorola, have yields as high as 50% (IBM) but the learning curve from aluminum to copper is characterized as "long, steep and expensive". (IBM, UMC Group and Motorola) (*EE Times*, July 5, 1999)

Advanced Sensors

A prototype device called a nuclear quadrupole system, which analyzes the energy waves of hidden mines, has been developed. The system penetrates the explosive material inside the land mine with RF energy. This excites the nitrogen atoms within the explosive material, causing the atoms to create a resonance that triggers an energy wave. This energy wave is computer processed and used to detect the presence of explosives. In initial tests, it has been far more accurate than existing mine detectors. During demonstrations in Bosnian minefields, the system found eight land mines with no false alarms. A traditional metal detecting system scored 34 false alarms. (Sponsored by DARPA) (*Defense News*, October 18, 1999)

Biological and Chemical Defense

A program on bioweapons defense is developing broad-spectrum antibiotics, effective against a wide range of microbes. (Sponsored by DARPA) (Isis Pharmaceuticals) (*Business Week*, November 1, 1999)

A binocular-mounted chemical sensor called a polychromator uses optics and MEMS to spot and identify different gases. It could detect poison gas up to two miles away. (Sponsored by DARPA) (Honeywell Technology Center, Sandia and MIT) (*Defense News*, September 6, 1999)

Biochips are being produced by building up vertical strands of DNA in successive layers. (Affymetrix) (*The Economist*, October 23, 1999)

Microelectronics

High volume production of digital ICs using transistors with 0.13-μm minimum feature sizes will be implemented by February 2000. (NEC) (*EE Times*, October 11, 1999)

Logic gates and memory elements based on molecular tunneling devices have been achieved. They fit between the wires used to address them. These switches cannot be used for RAMs but PROMs are possible. (Hewlett-Packard Labs and the University of California) (*Semiconductor International*, September 1999)

A half-adder circuit using molecular building blocks has been designed. (Mitre Corp.) (*EE Times*, November 15, 1999)

Fully functional state-of-the-art 64 Mbit DRAM devices, using 0.35μm line widths, have been fabricated on 300 mm diameter wafers. (Siemens and Motorola, Semiconductor 300 pilot line in Dresden, Germany) (*Semiconductor International*, June 1999)

Enthusiasm continues for the use of SiGe to achieve improved performance at a relatively low cost for both digital integrated circuits and RF wireless. IBM is the early leader in this technology but Lucent plans to pursue it vigorously as well. (Lucent Technologies Bell Labs) (*Solid State Technology*, November 1999)

A group of research scientists have developed a plotter capable of drawing lines that are only about 30 molecules wide and with only 200 billionths of an inch separating them. (Northwestern University) (*Business Week*, November 1, 1999)

A 1-volt digital signal processor has been produced that operates at a clock speed of 100 MHz. (Lucent Technologies, Inc.) (*EE Times*, November 8, 1999)

Progress during the last five years on wearable computers has been rapid. A fourth generation product weighs five pounds, retails for $5,000 to $7,000 and has a 200 or 233 MHz Pentium processor. Accessories include wrist-mounted keyboards and screens, as well as eyepieces and microphones. (Xybernaut Corp.) (*Military & Aerospace Electronics*, June 1999)

Advanced Materials

Advances are occurring in the development of giant magnetoresistance (GMR) materials. It is expected that the next major application of these materials will be for automotive components and electric motors. However, there is also a possibility of integrating GMR materials into standard CMOS processes. (Interuniversities Microelectronics Center (IMEC)) (*EE Times*, October 25, 1999)

A new ferroelectric material, bismuth lanthanum titanium (BLT) oxide has been developed. The compound seems to resist fatigue, which commonly occurs when PZT-based materials are used, in ferroelectric memory applications. (Seoul National University) (*EE Times*, October 25, 1999)

A physicist has discovered that ferroelectric materials are unusually sensitive to oxygen, the lack of which imperils their long-term durability. That effect may be employed to build a new kind of oxygen sensor. (Purdue University) (*EE Times*, July 12, 1999)

An erasable-rewritable optical memory that has the potential for storing up to 5 Gbit/cm^3 has been made from a photorefractive polymer. (Victoria University of Technology, Australia) (*Optics Letters* (24(14) 948).

Using InP crystals, researchers have shown that applied electric fields can channel light inside the crystal to create virtual optical fibers—i.e., an electrical field can confine a beam of light inside a crystal to form optical wires that stay the same size without the need for a waveguide. (University of Arkansas) (*EE Times*, June 14, 1999)

Researchers have developed ultrathin gate oxides for silicon based transistors—these layers of silicon dioxide are only 5 atoms thick. The researchers believe that 4 atoms thick is the achievable technology limit. (Lucent Technologies Bell Labs.) (*EE Times*, June 28, 1999)

Research groups have noted an apparently never-before-observed effect—the direct reversal of magnetic domains with an electrical field. This discovery may lead to a smaller, higher density storage system and a magnetic write head than can write up to 1000 times faster than present ones. (Cornell University and Swiss Federal Institute of Technology) (*EE Times*, August 23, 1999)

A native oxide for AlGaAs has been produced. It resulted in small, efficient, high performance VCSELs. (University of Illinois) (*Semiconductor International*, August 1999)

Using Hydride Vapor Phase Epitaxy (HVPE), GaN substrates have been grown on 2" diameter sapphire substrates and separated from the growth substrate by laser-induced liftoff. (Walter Schottky Institute and ATMI, Inc.) (*Compound Semiconductor* 5(4) May 1999)

The Air Force Research Laboratory has begun a Title III Wide Band Gap Materials Initiative aimed at increasing the wafer diameter of device quality SiC to 75 mm and eventually 100 mm. The Air Force is providing total funding of approximately $8 million and the three contractors participating in the program (Litton Airtron, Cree Research and Sterling Semiconductor) are providing matching funds. The program will continue through 2002. Both 4-H and 6-H N-type and semi-insulating material will be grown. Other objectives are to reduce production cost by 50%, increase boule size 100% and improve production yields by 50%. (Meeting notes ONR/DARPA Power Switching MURI Reviews, August 1999 and *Compound Semiconductor* November/December 1999)

Superconductors are being used to produce small, efficient, high torque, 1000 horsepower motors. (Reliance Electric Motor Group, a unit of Rockwell International) (*Business Week*, November 15, 1999)

Displays

A chip technology that consists of plastic (organic polymer) circuitry layered on top of thin flexible silicon sheets is being developed. If successful, it will result in displays so inexpensive that they can be discarded. (Cornell University) (*EE Times*, October 11, 1999)

Flexible displays containing organic light-emitting diodes and electronic ink are being produced. (IBM) (*EE Times*, October 25, 1999)

Electronic display paper is being produced and will be available for purchase soon. (E Ink and Lucent Technologies) (*The Economist*, October 30, 1999)

CMOS active pixel sensors have been used to produce a high-speed, high-resolution video camera. A 1024 x 1024 CMOS active pixel sensor array that can capture images at 500 frames per second is available for purchase. (Photobit Corp.) (*Aviation Week & Space Technology*, September 20, 1999)

Work is proceeding on a vision chip that uses an array of photodetectors with on-chip digital image-processing circuits. It acquires and processes images at 1,000 frames per second, enabling a robot arm equipped with a prototype sensor to grab for fast-moving objects without calculating trajectories. (University of Tokyo) (*EE Times*, August 9, 1999)

Visual Retinal Display technology is being considered for medical applications. One of these applications is non-invasive diagnosis of retinal diseases. (Microvision, Inc.) (*EE Times*, July 19, 1999)

Energy Storage Devices

The ultracapacitor is a new nanotechnology device. It uses electrically conductive powdered nitride and carbide to give its electrodes surface areas thousands of times greater than their apparent size. This provides high-energy storage and quick discharge/recharge capabilities. (T/J Technologies) (*Aviation Week and Space Technology*, November 8, 1999)

Micro-electrical-mechanical Systems (MEMS)

Fabrication of MEMS devices using polydiamond materials is underway. Polydiamond is of interest because it is extremely hard, has excellent chemical immunity, the highest thermal conductivity and very low friction. (University of Michigan) (*EE Times*, October 18, 1999)

A micromirror array chip is being used to create a "virtual mask" for performing photolithography. An array of 480,000 tiny aluminum mirrors reflects light onto just the areas of the substrate that would be illuminated through a conventional mask. (University of Wisconsin) (*EE Times*, October 18, 1999)

Lasers and Light Emitters

A semiconductor laser that emits light at two different wavelengths, 6.3µm and 6.5µm, has been developed. (Lucent Technology's Bell Labs) (*Optics.org Industry News*, October 27, 1999, SPIE and IOP Publishing Ltd.)

Blue laser emission at the 399-nanometer wavelength was recently achieved using a vertical cavity structure fabricated from gallium nitride. (University of Tokyo, University of Wurzburg and University of Leece) (*EE Times*, October 4, 1999)

A room-temperature light emitter based on GaN and AlN has been produced. It uses quantum dots grown on a silicon substrate. When 244-nanometer light or 325 nanometer light impinges on them, the quantum dots emit visible light. Depending on the size of the quantum dots, emitted light has a color ranging from blue to orange. (Centre National de la Recherche Scientifique) (*Laser Focus World*, October 1999)

System and Subsystem Applications

Micro air vehicles (MAVs) will make use of button-sized turbine engines being developed at MIT, MEMS chips and GPS equipment, cameras and transmitters. (Sponsored by DARPA) (*Defense News*, November 1, 1999)

DARPA plans to develop a miniature synthetic aperture radar—a microSAR for use on miniature unmanned air vehicles. It will make use of more than a dozen MMICs. (DARPA) (*Military & Aerospace Electronics*, August 1999)

A new autonomous landing guidance system is being developed that overlays millimeter-wave radar imagery on a cockpit heads-up display. The system's low-power, 94-GHz millimeter-wave sensor can work with any HUD that has raster capability. The sensor is designed to be mounted on the aircraft nose or in a small secondary radome near the cockpit. ALG has been flight tested on almost 500 approaches over the past four years by the USAF. (Marconi) (*Aviation Week & Space Technology*, June 7, 1999)

A MEMS-based computer that could withstand temperature and radiation extremes much better than electronic computers is being developed. (University of California, Berkeley and the Defence Evaluation and Research Agency, Malvern, England) (*The Economist*, September 11, 1999)

The Common Large Area Display Set (CLADS) has been built to be a low-cost, form/fit/function replacement for the E-3 Airborne Warning and Control System (AWACS) color monitor assembly, Airborne Battlefield Command and Control Center (ABCCC) airborne color display, the Joint Surveillance Target Attack Radar System (Joint STARS) graphics display unit, and the U.S. Navy E-2C Hawkeye Advanced Control Indicator Set (ACIS) display. The common design will reduce the cost of operation and maintenance by an estimated $3.3 million/year for the AWACS alone. The CLADS display is a rugged large area, 25 pound high-resolution color display head which can display color graphic, text and video data at various frame rates with 1280 x 1024 pixel full color groups. All data interfaces are digital. The CLADS head assembly can use COTS DMD, active-matrix liquid crystal displays, AC gas plasma, and electroluminescent displays. (Batelle Memorial Institute and U.S. Air Logistics Command, Warner Robins AFB) (*Military & Aerospace Electronics*, October 1999)

Flat panel displays, including helmet-mounted displays, are being used in military aircraft built by Boeing. (Boeing) (*Information Display*, August 1999)

A system called the Rotorcraft Pilot's Associate developed by Boeing will be tested in a Boeing Apache helicopter. It uses a digital terrain map to plot routes allowing minimal engagement time and providing safer entry and exit from combat areas. It is connected to a Longbow radar system and allows extracting maximum information with minimal radar emissions. It uses several other sensors to provide the pilot with additional information including an infrared targeting and acquisition system, JTIDS and a system called the Improved Data Modem. (Boeing) (*Aviation Week & Space Technology*, October 18, 1999)

An all-band laser source and fiber-optic technology is being used in infrared countermeasures (IRCM) applications. The fiber-optic cable used was developed by the U.S. Naval Research Laboratory to conduct the jamming energy from the laser through a modified ATIRCM jam head to the output aperture. The laser system generated more than 4 watts of jamming energy. (Sanders, a Lockheed Martin Company and NRL) (*Defense News*, November 22, 1999)

3. Special Technology Area Reviews (STARs)

Periodically, AGED conducts Special Technology Area Reviews (STARs) to better evaluate the status of an electron device technology for defense applications. STARs strive to elicit the applicable military requirements for a particular technology or approach while relating the present technology status to those requirements. The STAR culminates in a report that provides a set of findings and recommendations that the Office of the Secretary of Defense can utilize for strategic planning. The content of each STAR is tailored to extract the appropriate data through preparation of "Terms of Reference." STAR reports are, in general, available to the public, unless otherwise noted.

Since the last AGED report the following STARs have been conducted:

SUBJECT	DATES HELD	DATE REPORT ISSUED
Commercial-Off-The-Shelf (COTS) Electronic Components	December 4 and 5, 1997	June 1999
Frequency Control Devices	March 21 and 22, 1995	February 1996
Optical Interconnect Technology	May 11 and 12, 1995	March 1997 (For Official Use Only)
Micro-Opto-Electro-Mechanical Systems (MOEMS)	May 28, 1997	December 1997
Infrared Countermeasure (IRCM) Lasers	June 3 and 4, 1998	December 1999
The Future of Silicon Based Analog Integrated Circuits	Session 1: September 17, 1997 Session 2: December 11, 1997	TBD
Reliability of Electron Devices for Defense Applications	February 23, 1999	TBD

The following sections contain very abbreviated summaries of the findings and recommendations of these STARs:

3.1 Commercial Off-The Shelf Electronic Components (COTS)

- Appropriate use of COTS electronics components during development of new systems and system upgrades is essential to reduce costs in order to stay within shrinking acquisition budgets, maintain technology currency as system life cycles shorten and balance the needs for high system performance with acceptable costs.

- Although COTS usage will continue to expand, the need for military-unique components to maintain warfighter superiority will not disappear. There is and will continue to be a

need for the DoD to invest in electronics R&D. The benefits of this investment are clear and compelling.

- With the continually shrinking market for defense components, it is unlikely that commercial suppliers will develop military unique components without direct funding support and guidance from the DoD.

- The following are examples of defense unique components which will require continuing DoD R&D investment in order for the U.S. to maintain military superiority:
  - High performance, high frequency, wide bandwidth microwave electronics (2 to 200 GHz)
  - High bandwidth analog-to-digital converters (0.5 to 20 Gsps)
  - Devices and components for operation at very high temperatures
  - Electro-optic IR imaging arrays, EO components for missiles, and related components
  - UV/IR Detectors
  - Radiation-hardened integrated circuits for space
  - High power RF sources - solid-state and vacuum (5 to 100 GHz, 1 to 1000 Watts)
  - MEMS for miniature UAVs
  - Electronically steered antenna arrays for multiple agile beam forming
  - High performance, highly integrated packaging and interconnect MCM technologies

- Without an enhanced continued U.S./DoD S&T investment in these types of military-unique technologies, the military superiority the U.S. has enjoyed in the latter part of the 20th century will gradually disappear in the 21st century, simply because superiority translates to time lead. This 5 to 10 year time lead must be provided by unique technology that is not available to potential U.S. adversaries, and difficult to reverse engineer in a short period of time.

- It is desirable to make use of commercial processes and practices, to the maximum possible extent, to produce needed military-specific electronics parts.

- A clear U.S. and DoD long-term policy of support for robust military-essential electronics science and technology investment should be established by the DDR&E with Service concurrence.

3.2 Frequency Control Devices

- Frequency Control Device Technology is of vital importance to the DoD since the accuracy and stability of frequency sources and clocks are key determinants of the performance of radar, C^3I, navigation, surveillance, EW, missile guidance and IFF systems.

- Presently (in 1995), however, funding for frequency control devices is grossly inadequate. DoD requirements, both present and future, will go unmet as a consequence of that funding shortfall. The group therefore recommends that funding for frequency control devices be increased to a level that will be sufficient to revitalize and sustain a DoD-specific technology base, ensure availability of industry vendors to service DoD needs, and stimulate new university and industry R&D activity.

- High performance frequency control devices are vital components of a large number of high priority DoD systems. They represent an enabling technology upon which the satisfactory performance of systems such as GPS, MILSTAR, Joint-STARS, AMRAAM, and many classified programs are dependent.
- Unmet, DoD-unique requirements exist in these areas:
  - high-accuracy low-power clocks
  - low-noise vibration-resistant oscillators
  - gun-hardened oscillators/clocks
  - radiation-hardened oscillators
  - man portable, real time, chemical and biological sensors
- An adequate manufacturing infrastructure must be put into place to assure the availability of required frequency control components, at an affordable cost, as needed for DoD system use. The R&D and industrial bases have eroded drastically—to the point where systems have begun to encounter difficulties obtaining the required frequency control devices. This trend is likely to accelerate as companies who previously specialized in DoD business shift their focus to commercial markets.

The payoff from these activities will be the ability to field systems such as GPS, MILSTAR, Joint STARS, Patriot, AMRAAM, JTIDS and many others with greatly improved performance characteristics, including increased accuracy and range. In addition, system reliability will be enhanced and costs minimized.

3.3 Micro-Opto-Electro-Mechanical Systems (MOEMS)

- MOEMS offer the capability to fabricate a variety of devices.
- MOEMS have significant potential for use in military systems.
- Commercial opportunities exist for MOEMS, particularly in the display arena.
- Existing fabrication lines can be easily adapted for MOEMS production.
- This technology presents an opportunity for revolutionary new optical designs that can offer a competitive military advantage.
- As devices emerge, the committee recommends that export controls must be carefully planned in recognition of both the significant foreign investment in this technology and the necessity to maintain a large industry production base to lower device costs.
- The constitution of military service representatives to champion this technology and develop system requirements is deemed an essential recommendation of this committee to properly exploit the technological advantage.
- From this Service team, with the participation and leadership of DARPA, the committee recommends that a coordinated technology roadmap and plan for system insertion be prepared.

3.4 Infrared Countermeasure (IRCM) Lasers

- Anti-aircraft and anti-ship missiles are becoming a major concern for all services.

- New and more advanced missiles are on the horizon.
- Most promising IRCM laser approaches are in the 6.2 status.
- There are no programs planned to carry the DARPA/Navy lasers to packaged demonstrators.
- IRCM laser development activities in industry may be declining.
- Life-cycle costs are difficult to quantify.
- Great strides are being made in some laser development areas.

Based on these findings, the committee recommended specific high payoff 6.1 and 6.2 laser S&T efforts and additional funding for reliability and packaging of existing lasers such as the DARPA/Navy Mid-IR product.

APPENDICES

Appendix A: Funding Category Definitions

6.1 – Basic Research

Systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind.

6.2 – Applied Research

Systematic study to gain knowledge or understanding necessary to determine the means by which a recognized and specific need may be met; a systematic application of knowledge toward the production of useful materials, devices, and systems or methods including design, development, and improvement of prototypes and new processes to meet specific requirements.

6.3 – Advanced Technology Development

All efforts that have moved into the development and integration of hardware for field experiments and tests. The results of this type of effort are proof of technological feasibility and assessment of operability and producibility rather than the development of hardware for service use. Projects in this category have a direct relevance to identified military needs.

Appendix B: AGED Responsibilities

To help ensure that its needs are met, DoD has chartered AGED to perform a number of vital functions, including:

- Facilitating the development of and maintaining a comprehensive DoD electronics technology strategy

- Advising DoD management on electronics S&T investment, technology and funding matters

- Advising on the production, use, infrastructure and supply aspects of critical electronic components for the defense electronics supply base.

- Advising on significant advances/discoveries or problems that may impact device availability dates.

- Assessing present and planned electron device development programs of the Military Departments to ensure their consistency with the performance and cost requirements of future military systems.

- Coordinating U.S. electronics technology development by providing a medium for the interchange of information within DoD, between DoD and other agencies of the Federal Government performing related work, and between DoD and Government contractors (industry and universities).

- Establishing and maintaining “bridges” between system developers, the Manufacturing Technology (MANTECH) community and basic research community

- Promoting coordination and outreach with industry, Government and academia for its DoD customers

- Undertaking other appropriate tasks assigned by the Office of the Under Secretary of Defense (Acquisition and Technology), such as specialist support for the OSD staff, the Military Departments and the Defense Advanced Research Projects Agency (DARPA).

- Assisting the Joint Directors of Labs (JDL) Project Reliance Technology Panel for Electronic Devices (TPED) in strategic planning of the tri-Service electron device program.

- Conducting special reviews of selected technology areas and assessing their potential usefulness in military systems.

Appendix C: Principal AGED Members

Executive Director

Dr. Susan Turnbach, ODUSD(S&T)/SS

Main Group

Consultant Members

Mr. Jack Kilby, Chairperson Emeritus, Consultant, Inventor of Integrated Circuit
Dr. Tom Hartwick, Chairperson, Consultant, former Chief Scientist, TRW
Dr. Barry Dunbridge, Chief Scientist, TRW
Dr. George Heilmeier, Chairman Emeritus and former Chief Executive Officer, Bellcore (now Telcordia Technologies)
Dr. William Howard, Consultant, former Senior Vice President, Motorola
Mr. Leonard Weisberg, Consultant, former Senior Vice President, Honeywell

Service Members

Dr. John M. Pellegrino, Director, Sensors and Electron Devices Directorate, U. S. Army Research Laboratory
Dr. Ingham A. Mack, Program Manager, Office of Naval Research
Mr. Robert Kemerley, Chief, Aerospace Components Division, Sensors Directorate, Air Force Research Laboratory
Mr. Edward Reiss, U.S. Army Research Laboratory
Dr. James Ratches, U. S. Army CECOM Night Vision and Electronic Sensors Directorate
Dr. Gerald M. Borsuk, Superintendent, Electronics Science and Technology Division, Naval Research Laboratory
Dr. Robert D. Pugh, Chief, Space Electronics Branch, Space Vehicles Directorate, Air Force Research Laboratory

Working Group A

Consultant Members

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Dr. Peter Asbeck, Professor, University of California—San Diego
Mr. Jon Christensen, Business Development Manager, Hughes Electron Dynamics Division
Dr. Linda Katehi, Professor, University of Michigan
Dr. George P. Rodrigue, Regents' Professor Emeritus, ECE, Georgia Institute of Technology
Dr. Joseph A. Saloom, Technology Consultant, former Senior Vice President, M/A-COM

Service Members

Mr. H. Bruce Wallace, Branch Chief, Sensors & Electron Devices Directorate, U.S. Army Research Laboratory
Dr. Robert K. Parker, Head, Vacuum Electronics Branch, Naval Research Laboratory
Mr. Mark Calcatera, Chief, RF Components Branch, Air Force Research Laboratory
Dr. John R. Vig, U. S. Army CECOM

Dr. Kenneth J. Sleger, Associate Superintendent, Electronics Science and Technology Division, Naval Research Laboratory
Mr. Leonard H. Vanzant II, Microwave Systems Directorate, Naval Surface Warfare Center—Crane
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Working Group B

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Dr. Conilee Kirkpatrick, Chairperson, Senior Vice President, HRL Laboratories
Mr. James Clary, Vice President Electronics and Systems, Research Triangle Institute
Dr. Barry Gilbert, Staff Scientist, Mayo Foundation

Service Members
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Dr. Joseph M. Killiany, Branch Head, Naval Research Laboratory
Mr. Alan Tewksbury, Chief, Multichip Integration Branch, Air Force Research Laboratory
Dr. Isaac Lagnado, U. S. Navy SPAWAR
Mr. Victor Brunamonti, Manager, Component Engineering, Naval Surface Warfare Center—Crane
Mr. Ronald Bobb, Air Force Research Laboratory
Dr, Dan Radack, Program Manager, DARPA Microsystems Technology Office
Dr. Les Palkuti, Defense Threat Reduction Agency
Dr. David Myers, Deputy Director for Defense Programs, Microsystems Science Technology and Components, Sandia National Laboratories

Working Group C

Consultant Members
Dr. Andrew Yang, Chairperson, Consultant, former DARPA Program Manager
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Appendix D: Key Capabilities and Requirements

KEY REQUIRED CAPABILITIES	FUNCTION
Development of High Performance Microwave and Millimeter Wave Integrated Circuits and Related Packaging and Interconnection Technology	To provide superior transmitting and receiving capabilities for systems such as radars, electronic countermeasures, missiles, smart weapons and communications. To enable unmanned airborne vehicle (UAV) radars, electronic decoys, secure ultrahigh-capacity wireless communications, and smart weapons.
Analog-to-Digital Converters With a High Number of Effective Bits, Wide Bandwidth and Large Spur-Free Dynamic Range	To realize broadband, high dynamic range direct digital receivers for multi-functional systems, including communications, radar and EW; to realize significant reductions in cost, size, weight and power by digitizing input signals as close to the receiving antenna as possible.
Exploration of Photonic Solutions for High Performance, Multi-Sensor Active Arrays, Higher Performance Computing and Memories	To provide exceptionally large bandwidth capabilities or true time delay capabilities enabling higher accuracy, high-resolution systems not otherwise feasible.
Advanced Microelectronics Device and Circuit Developments	To enable signal and data processors capable of processing orders of magnitude larger amounts of information in orders of magnitude shorter periods of time. To assure that needed advances in radiation-hardened device/circuit technology occur so that critical components for systems that must operate in severe radiation environments are available.
High-Resolution Miniature Displays	To provide accurate and easily updated visual information to battlefield commanders, the soldier in the field, the medic in a remote-site hospital and the pilot on a mission.
Focal Plane Arrays (Cooled and Uncooled) and Improved UV/IR Detectors	To provide enhanced discrimination against low visibility targets
High Power Lasers	To meet IR countermeasure needs.

KEY REQUIRED CAPABILITIES	FUNCTION
Microelectromechanical Systems (MEMS) For Miniature Sensors And Actuators	For safer, more capable vehicles and aircraft, more cost-effective manufacturing and the ability to perform many mechanical system functions with components that are a small fraction of the size and weight of existing devices. To enable special purpose microwave functions.
Integration of Mixed-Signal Integrated Circuit Technologies (including development of interconnection and packaging approaches that allow reliable, efficient integration of microwave/millimeter wave, IR, analog, digital and MEMS devices and circuits; including development of CAD tools, languages and equipment to allow efficient appropriate selection and integration of best choices of electronic (photonic) components for particular missions)	To enable miniature RF/digital receivers for multifunction radar/ESM/CNI sensors. To produce compact, lightweight, low-power, very high performance, high reliability integrated electronic equipment suites.
Materials for High Temperature and Adverse Environment Operation (such as silicon carbide and gallium nitride)	To meet DoD system needs in severe operating environments.